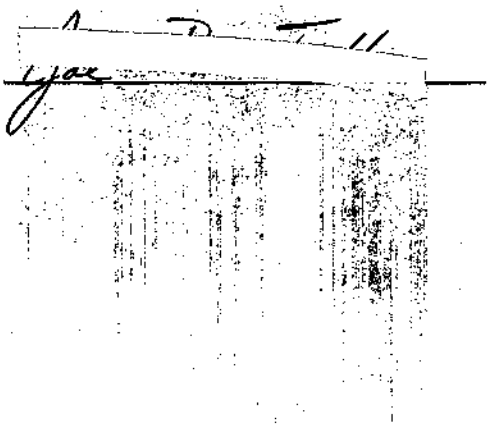
In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institution shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.



MESOPHILIC STAGE DIGESTION AT ATYPICAL LOADINGS

A THESIS

Presented to

The Faculty of the Graduate Division

by

Joe Paul Teller

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Sanitary Engineering

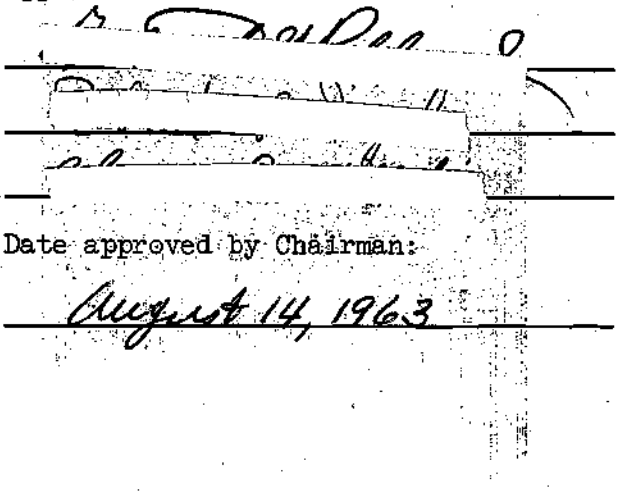
Georgia Institute of Technology

August, 1963

3R
12

MESOPHILIC STAGE DIGESTION AT ATYPICAL LOADINGS

Approved:



Date approved by Chairman:

August 14, 1963

ACKNOWLEDGMENTS

The writer expresses sincere appreciation to Dr. F. G. Pohland, his thesis advisor, for his guidance and encouragement throughout this study. Further gratitude is expressed to Dr. R. S. Ingols and Dr. C. R. O'Melia, members of the thesis reading committee, for their constructive suggestions.

The spirit of cooperation shown by K. M. Ries and other fellow students is gratefully acknowledged.

The writer wishes also to thank the Texas State Department of Health for its assistance and material support during the research and graduate study culminating in this thesis.

A special acknowledgment of appreciation is expressed to the writer's wife, whose moral support and sacrifices, not to mention the typing of rough and final drafts, encouraged the writer throughout his graduate program.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
LIST OF TABLES	iv
LIST OF ILLUSTRATIONS	v
SUMMARY	vi
Chapter	
I. INTRODUCTION	1
II. REVIEW OF LITERATURE	4
III. EXPERIMENTAL APPARATUS	15
IV. ANALYTICAL METHODS	21
V. EXPERIMENTAL PROCEDURE	23
VI. EXPERIMENTAL RESULTS	28
VII. DISCUSSION OF RESULTS	38
VIII. CONCLUSIONS AND RECOMMENDATIONS	43
APPENDICES	
A. TOTAL VOLATILE ACIDS BY COLUMN CHROMATOGRAPHY	46
B. DEWATERING INDEX	48
C. OBSERVATIONS ON THE VOLATILE ACID DETERMINATION METHOD	50
D. SUMMARY OF BASIC DIGESTION DATA	52
BIBLIOGRAPHY	72

LIST OF TABLES

Table		Page
1.	Chemical Composition of Sludges	5
2.	Average Chemical Constituents of Sludges	6
3.	Phase Summary, Unit 1	30
4.	Phase Summary, Unit 3	31
5.	Phase Summary, Unit 2	32
6.	Phase Summary, Unit 4	33

LIST OF ILLUSTRATIONS

Figure		Page
1.	Temperature Effect on Digestion Rate	8
2.	Complete Digestion Unit	16
3.	Digestion Bottle, Mixing Seal	17
4.	Circuit Diagram for Gas Collection Device	19
5.	Biochemical Environment, Units 1 and 3	34
6.	Biochemical Environment, Unit 2	35
7.	Biochemical Environment, Unit 4	36
8.	Overall Indices	37

SUMMARY

In order to investigate the effects of unusually high organic loading rates on a mesophilic digestion system laboratory studies were conducted on a system closely simulating conventional two-stage digestion.

Four seven-liter units were operated for 121 days, with two units as first and two as second stage digesters. Raw primary sludge from a local sewage treatment facility was used for feed material and the final loading to the system was greater than six times the loading of 0.1 pounds of volatile solids per cubic foot currently used in digestion practice. These heavy loads were accommodated by the system with no loss in overall digestion efficiency. Actually, this heavier loaded system was more stable with respect to shock loads of organic matter. This system was achieved with detention periods as low as 7 days in the first-stage units and 20 days in the second-stage units.

Digestion indices determined were: total solids, volatile solids, alkalinity, volatile acids, pH, ammonia nitrogen, dewatering ability, total gas production, and CO_2 content of the evolved gas.

It was found that in increasing incremental loadings each fourth day by 0.04 pounds of volatile solids per cubic foot per day, the increase could be tolerated without digestion difficulties, provided adequate mixing and heating were provided. Even at the extreme loading rates used, digestion continued at a normal rate, with pH values above 7.3 and volatile solids reduction averaging greater than 60 per cent.

As volatile matter loading increased, ammonia nitrogen and alkalinity concentrations also increased, but volatile acids remained relatively constant, at no time being greater than 700 mg per l as acetic acid. It is believed that the degree of mixing, as well as maintenance of an optimum temperature, resulted in an unusually well-balanced biological environment, thus preventing a build-up in volatile acid concentration.

Operating at these elevated loadings, it was found that the digesters were less susceptible to upsets resulting from high shock loads of organic material than those operating at conventional loading rates. It is felt that this resistance to upset is the result of a larger, more active bacterial population, which cannot be achieved at conventional loading rates.

CHAPTER I

INTRODUCTION

In conventional domestic sewage treatment sludge digestion often causes considerable difficulties. Digester malfunction takes on many forms and is caused by a variety of conditions. Foaming, scum blankets, slow digestion, and excessive odors all are reported, and the causes of these problems range from too much feed to insufficient feed, under-design to over-design, inadequate mixing, toxic materials, and undefined causes.

Any biological process by its very nature must be a complex system. The anaerobic digestion of sewage sludge is no exception and is of such a nature as to make investigation of the system somewhat difficult. Since anaerobic systems require the absence of free oxygen, some study techniques are difficult to apply.

At this time, a complete understanding of the biological and/or biochemical processes involved in sludge digestion is not available. A biological system does exist and under most conditions functions in a balanced manner. However, because of this incomplete understanding, we are unable to exercise complete control over the system, nor can we always successfully predict impending difficulties.

Sludge digestion may be defined as the anaerobic decomposition of organic matter. This process can be considered to occur in two phases. In the first phase, complex materials are decomposed by bacterial and

and biochemical action into less complex materials, including volatile acids. The second phase of digestion consists of a breakdown of these less complex materials into gaseous products, mainly carbon dioxide and methane.

The initial acid formation results in a pH depression when the acid concentration becomes sufficiently high. These high concentrations of volatile acids retard the activity of those organisms which produce carbon dioxide and methane. For an anaerobic system to function properly, a balance of organisms must be achieved, and this balance may be upset since the sensitive methane-forming bacteria are easily inhibited by high volatile acid concentrations.

As the methane-forming organisms attack the acids and release gas, alkaline by-products are formed which can then react to neutralize the volatile acids. These alkaline by-products include salts such as ammonium, calcium and magnesium bicarbonates, and are formed--as an example, when NH_3 combines with CO_2 and H_2O. The acids which are present normally exist as acid salts, arising from a combination between acids and the products of protein breakdown.

In a balanced system the alkaline materials formed will be sufficient to maintain neutral or near-neutral conditions in the digester.

This study was undertaken to gather more information on the volatile acid-alkalinity relationship at unusually high loadings. Should a biological or biochemical imbalance develop external control will be utilized to re-establish the balance of the system. It is expected that in the course of the study other relationships will be observed and these relationships, along with the volatile acid-alkalinity data should result

in a more complete understanding of the anaerobic digestion process, and factors affecting its performance.

CHAPTER II

LITERATURE REVIEW

Introduction

It is not the purpose of this literature review to cover all available information concerning anaerobic decomposition of sewage sludge, but rather to provide a basic review of the subject with particular attention to the areas closely related to this study. Pohland (1) has recently compiled a general review of the subject which is comprehensive in its coverage of the field. Other general literature reviews are compiled yearly by the Water Pollution Control Federation and are published in their monthly journal. The following review will be directed toward a discussion of the available literature concerning the anaerobic process, methods utilized for control of the process, and initially, composition of the substrate involved.

Substrate Composition

Based on studies conducted by Rudolfs and Gehm (2), Tables 1 and 2 give a description of the composition of sludges.

The various constituents will vary from location to location, as will dry solids, organic matter, volatile material, etc. Dry solids will, however, average 70 per cent organic and 30 per cent mineral matter in fresh solids, while digestion changes their values to 40 per cent organic and 60 per cent mineral matter (3).

Table 1. Chemical Composition of Sludges (Per Cent of Dry Solids) (After Rudolfs and Gehm (2))

Constituent	Plain Settled	Digested	Activated
Organic matter	60-80	45-60	62-75
Total ash	20-40	40-55	25-38
Insoluble ash	17-35	35-50	22-30
Pentosans	1.0	1.5	2.1
Grease and Fat (Ether soluble)	7-35	3-17	5-12
Hemicellulose	3.2	1.6	-----
Cellulose	3.8	0.6	
Lignin	5.8	8.4	
Protein	22-28	16-21	32-41

Mechanism

Anaerobic sludge digestion can be represented by the reaction:

$$CHX + H_2O \longrightarrow CO_2 + CH_4 + X \quad .$$

This is the ideal removal of carbon, resulting in the formation of two gases and a stable humus (4). In this equation the letter X is used to represent those portions of organic matter which are neither carbon nor hydrogen. To carry this process to completion, several steps, or phases, are necessary. These steps are often referred to as liquefaction, gasification, mineralization, and humidification (5).

Liquefaction is the transformation of solid particles of sludge into either a soluble or finely dispersed condition (6). Anaerobic organisms attach to the solid particles and through their extracellular enzymes, attack the sludge particles, and reduce them to forms acceptable to subsequent gasification. Following liquefaction, gasification commences with mainly methane and carbon dioxide being formed. The materials remaining from liquefaction are attacked intracellularly by the gasification organisms (often called

Table 2. Average Chemical Constituents of Sludges (Per Cent of Dry Solids) (After Rudolfs and Gehm (2))

Chemical Constituents	Chemical Symbol	Plain Settled Sludge	Digested Sludge	Activated Sludge
Nitrogen	N	4.5	2.25	6.20
Phosphorous	P_2O_5	2.25	1.50	2.50
Potassium	K_2O	0.50	0.70	0.75
Silicon	SiO_2	13.80	27.60	8.50
Iron	Fe_2O_3	3.20	6.00	7.20
Aluminum	Al_2O_3	2.10	4.30	3.20
Calcium	CaO	2.70	4.70	1.70
Magnesium	MgO	0.60	1.00	1.40
Manganese	MnO	0.02	0.04	0.03
Sodium	Na_2O	0.80	1.50	1.00
Titanium	TiO_2	0.06	0.10	0.08
Copper	CuO	0.02	0.05	0.05
Barium	BaO	0.05	0.10	0.06
Zinc	ZnO	0.01	0.04	0.03
Lead	PbO	0.10	0.20	0.20
Nickel	NiO	----	----	0.005
Cobalt	CoO	0.0002	----	0.0002
Sulfur	SO_3	1.2	2.5	2.90
Chlorine	Cl_2	0.5	0.60	0.50
Chromium	Cr_2O_3	-----	----	0.20
Arsenic	As_2O_3	Trace	Trace	0.013
Boron	B_2O_3	-----	-----	0.0115
Iodine	I	-----	-----	0.001

methane formers) and while both processes occur simultaneously, some liquefaction precedes the gasification phase. These two phases must be synchronized, for if liquefaction proceeds faster, the accumulation of liquefaction products can retard gasification.

The methane and carbon dioxide formed in the gasification phase are generally considered to compose the bulk of the gas produced. According to Langford (7), gas production averages 7 to 12 cubic feet of gas per pound of volatile solids added and has the following composition:

Carbon Dioxide	25-35 per cent
Methane	50-68 per cent
Hydrogen	1-5 per cent
Nitrogen	2-7 per cent
Oxygen, Argon, etc.	trace amounts

The listed percentages of hydrogen and nitrogen are probably the maximum reported values, since these constituents normally are in the fractional parts.

Mineralization and humidification follow, converting organic matter to elemental minerals in a black humus. There is no clear line of demarcation separating these phases, but a great deal of overlapping and concurrent action occurs. Buswell (8) considers the overall digestion as occurring in two stages - an initial acid stage and a latter alkaline stage. McKinney (9) concurs with the two stage concept, but calls the second stage the methane stage. Sawyer (10) is in agreement with the two phase concept indicating that the saprophytic organisms (acid formers) and methane formers live harmoniously in the same environment. The saprophytic organisms convert complex organics into simpler organics, including acids. The acids are

converted by the methane formers to methane and CO_2.

Temperature

Temperature changes have a great influence on sludge digestion, primarily because of accelerated bioligical reaction rates which occur at increased temperature within limits. Figure 1 shows the effect of temperature on the rate of sludge digestion as reported by Fair, Moore and Thomas (11).

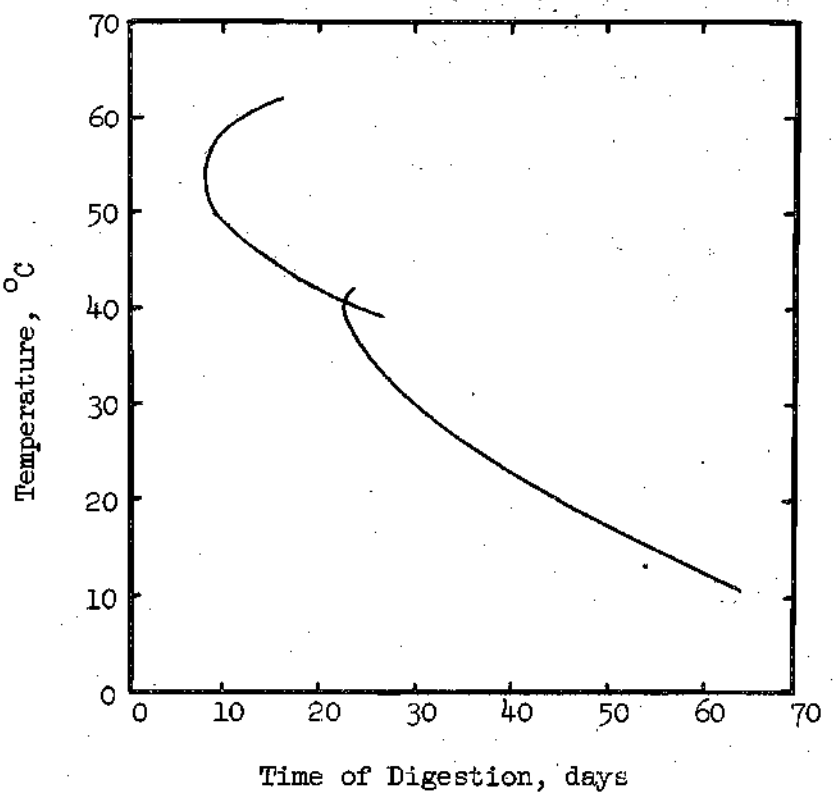


Figure 1. Temperature Effect on Digestion Rate (After Fair, Moore and Thomas (11))

Of the various classifications of bacteria in an anaerobic system, the grouping based on operating temperature is most generally accepted. The broad divisions are (12):

Below 20°C - Psychrophilic (cryophilic)

20°C - 45°C - Mesophilic

Above 45°C - Thermophilic

Buck, Keefer and Hatch (13) report the thermal death at 67°C of one of the liquefying organisms found in digested sewage sludge (Streptococcus diploidus). Golueke (14) reports that very little difference in activity is noted in the 35-60°C range and that little, if any, activity exists at 65°C. Garber (15) reports that the 39°C culture is very stable, while Golueke (14) indicates that the 50-60°C range is slightly better. Rudolfs and Heukelekian (16) noted that adequate digestion in 2.1 days could be achieved at 50°C. Langford and Buswell (4) agree that a temperature variation of plus or minus 2°C should be considered as a maximum deviation, and Shafer (17) states that it is essential to bring a digester to optimum temperature as soon as possible when starting. Golueke (14) reports there was no significant difference in volatile material reduction, volume, or composition of gas or nature of acids produced in samples taken from digestion temperature ranges of 35-60°C although pH and acid concentration did increase slightly with temperature.

Mixing

Limited mixing, by virtue of the rising gas bubbles, is the natural result of active digestion, but modern practice calls for a more thorough mixing. Buswell (4), Fuhrman (18), Garber (15), Keefer (19), and Rudolfs and Heukelekian (16) all point out the necessity for adequate mixing. Mixing is important from several aspects, both biological and mechanical. Primarily, food and organisms are brought into the necessary intimate contact, while at

the same time the waste products of bacterial metabolism are removed from the point of their origin, thereby precluding any excessive accumulations of these harmful products (6).

Steel (20) states that, in conventional digestion, the acid forming bacteria tend to concentrate in the scum layer, while the methane formers concentrate in the lower sludge layer. Mixing will prevent these concentrations, provide a more homogenous system, and allow the necessary food-organism contact to occur. Schreiber (21) found no significant variation in alkalinity, solids, volatile acids, or pH between samples taken at the bottom and the upper portion of a digestion tank. Guarino (22), reporting on the operation of large digesters serving the city of Philadelphia, states, that, in addition to other disadvantages, limited mixing facilities lead to a loss of usable digester volume through decreased digestion efficiency. Schreiber (23) discusses extensive mixing at the District of Columbia sewage treatment plant where thickened sludge is undergoing high rate digestion in twelve digesters. Both internal mixing devices and sludge recirculation are used, and four different methods of internal mixing are used and described.

Seeding and Additives

The addition to raw sludge of sludge which has been actively digesting will materially shorten the time required to establish an active digestion process. In addition, seed material provides a buffer against overproduction of volatile acids during the initial digestion "start-up" period. In conventional digestion practice seeding involves the retention of digested sludge in the digester at all times. As previously indicated, mixing is required. Keefer (19) points out that raw solids can be digested in about ten days if

the weight ratio of digested volatile solids to raw volatile solids is maintained at 1:1.

Shafer (17), Langford (7), and Steel (20) all mention the necessity for adequate seed material to maintain the necessary environment. Heukelekian and Berger (23) indicate that all the bacteria necessary for digestion are present in raw sewage solids, while Grune (24) showed that the digestion period required for batch digestion of sewage sludge would be reduced up to tenfold by adequate seeding.

The use of additives has been restricted primarily to lime. The literature is rather confusing at this point; it is a simple matter to find divergent opinions as to the merits of lime usage. The issue is still unresolved and will very likely continue to be a controversial subject for years. McCarty and McKinney (25) state that lime is an excellent material for neutralization because of its low toxicity. Sawyer, et al. (10) found that lime dosage at 200 per cent of the volatile acids content proved effective, but reported difficulty in mixing lime with the sludge. Shafer (17) concurs with the 200 per cent figure, noting that its application produced the desired results after a digester failure. Cassell and Sawyer (26) report on lime used to maintain pH from 6.8 to 7.2 when starting digesters. In contrast to this view, Kaplovsky (27) and Barker (28) contend that the addition of alkalies should not be used for volatile acid control. Schulze and Raju (29) state that the neutralizing of acids does not restore methane bacteria activity. Heukelekian and Berger (23) report that the addition of pure enzymes, enzyme and bacterial preparations, and yeast does not enhance the liquefaction of solids as measured by the B.O.D. of the supernatant. Keefer, et al. (30) have shown that raw sludge, seeded with Streptococcus diploidus underwent

digestion over a wide pH range. In a subsequent report on the same topic, Keefer, et al. (31) report that at optimum conditions Streptococcus diploidus is incapable of gasifying sterilized sludge and that no relationship exists between gas production and the amount of Streptococcus diploidus added to raw sludge.

Volatile Acids

The concentration of volatile acids in a digester as an index of digestion is generally recognized and supported by Kaplovsky (27), Mueller, et al. (31), Sawyer, et al. (19), Schulze and Raju (29), Shafer (17), Barker (28), and Schultz (33). Should the volatile acids which are formed accumulate faster than they can be converted to methane, the methane formation will be arrested (11). The concentration of the acids, measured as acetic acid, which will retard or inhibit methane formation is generally accepted to be around 2,000 mg per l for conventional digestion practice (6), (11), (12), and (13). Buswell (34) infers that a twenty-four hour increase of 200-300 mg per l is more of a danger sign than the 2,000 mg per l limit. Sawyer (35) reports a 100-250 mg per l volatile acids content (expressed as acetic acid) to be the normal operating level in digesting sludge.

Considerable work has been done on volatile acid determination methods as reported by Mueller, et al. (36), (37), Elsden (38), Frook (39), Heukelekian and Kaplovsky (49), Ramsey and Patterson (41), Buswell, et al. (42), DiLallo and Albertson (43), Manganelli and Brofazi (44). While the current edition of Standard Methods (45) does not include any but distillation methods, considerable work involving volatile acid determinations is being done using a chromatographic method. The principle involved is simple and excellent recovery is reported (36).

Digestion Control

Researchers and authors, by virtue of experiments and experiences, have been able to define optimum conditions and limiting factors encountered during digestion. The degree of agreement of these parameters is surprising considering the variety of sludges, operating conditions, and experimental methods. A listing of those factors of interest at this time include:

pH	range	6.8 - 7.2 (26)
Volatile acids	maximum	3000 mg/l as acetic acid (23), (25)
Solids concentration	maximum	15 per cent (29)
Ammonia nitrogen	maximum	1250 mg/l as NH_3 (46)

Nash and Chasick (47), reporting on high rate digestion, state that volatile solids loadings of 0.15-0.38 lb per cu ft per day of digester capacity were digested with a 57 per cent destruction in volatile matter. McKinney (9) notes current digester design is on the basis of 0.1 lb V.S. per cu ft per day, (for explanation of "V.S.", see Chapter IV) while Steel (20) lists values of .02-.06 pounds. Pohland (6) encountered retarded digestion at a volatile solids loading of 0.2 lb per cu ft per day, and Babbitt and Baumann (48) recommend loadings of approximately 0.05 to 0.25 lb V.S. per cu ft per day of tank volume.

It is generally accepted by investigators that an increase in volatile acids is one of the first signs of impending digester difficulties. It is also agreed that the volatile acid build-up is a result of unbalanced digester condition, but there the agreement stops. The actual effect on the digestion process by high volatile acid concentrations is a subject which could well prove to be as controversial as the value of liming.

McCarty and McKinney (49) state that decreased activity of the methane formers is casued by salt toxicity, not direct volatile acid toxicity. They contend that the toxicity arises from the cation portion of the volatile acid salt. On the other hand, Pohland and Bloodgood (50) present the development of the "volatile acid-salts" alkalinity relationship which indicated that whenever the "volatile acid-salts" alkalinity surpassed the total alkalinity, free volatile acids were present and associated decreases in pH and a general inhibition of the digestion process could be expected. Still another view is held by Schulze and Raju (29) who believe that toxic conditions are independent of pH, and that a volatile acid concentration of about 2000 mg per l is an upper limit. Kaplovsky (23) feels that volatile acids are toxic only in an indirect manner through a pH reduction, and can be relieved by the use of a neutralizing agent.

McCarty and McKinney (25) report that up to 16,000 mg per l acetate salts, as acetic acid, were successfully digested in a batch digestion process. However, the seed sludge used had been previously acclimated to 2000 mg per l of acetic acid. McKinney (9) states that the upper limit of digestion will be dependent on the concentration of the ammonium ion. In a later article, McKinney (25) admits that the high concentration of ammonia necessary to produce toxic conditions is not normally encountered in conventional digestion operation.

CHAPTER III

EXPERIMENTAL APPARATUS

An illustration of one of the digestion units, complete with the gas collection arrangement, is shown in Figure 2. Four of these units were used; with gas, water, and electrical connections being identical for each unit. A 9-liter Woulff bottle with three openings at the top and one at the bottom was used for each digester, with the openings used as illustrated in Figure 3. All four digesters were housed in an incubator in which two 150-watt light bulbs served as a heat source. This incubator was fitted with a continuous duty recirculating fan and a thermoregulator for temperature control. Four plexiglass windows were installed to allow visual observation of the digesters and styrofoam was used to completely insulate the interior of the unit.

The mixing shaft was constructed of a 1/4-inch stainless steel rod; the blades were made of 1/4-inch plexiglass spaced so that the top blade served as a scum breaker when the unit was at operating capacity. All four stirring rods were driven from a common drive shaft which was powered by a variable speed AC-DC motor. The drive shaft was held in position by pillow block bearings and power was transmitted to the stirring rods through a worm to worm gear arrangement. Operating speed of the paddles, measured at the shaft, was 60 RPM during mixing.

To measure the gas produced during digestion the apparatus illustrated in Figure 2 was employed. The unit consisted of two 20-liter carboys, one serving as a gas collection bottle, with the other being the water displacement and measurement bottle. The gas bottle was sealed with a two-hole rubber

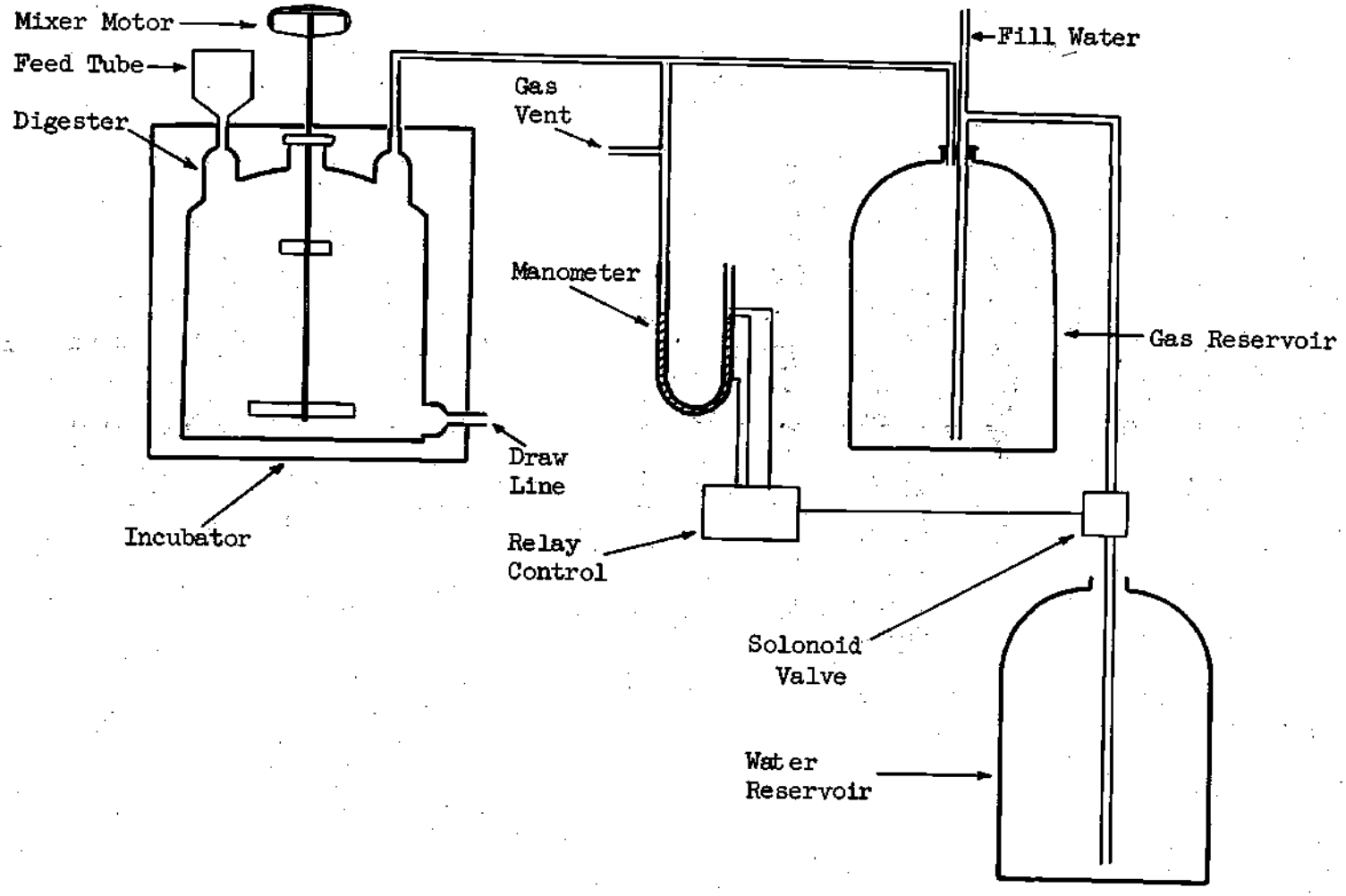


Figure 2. Complete Digestion Unit

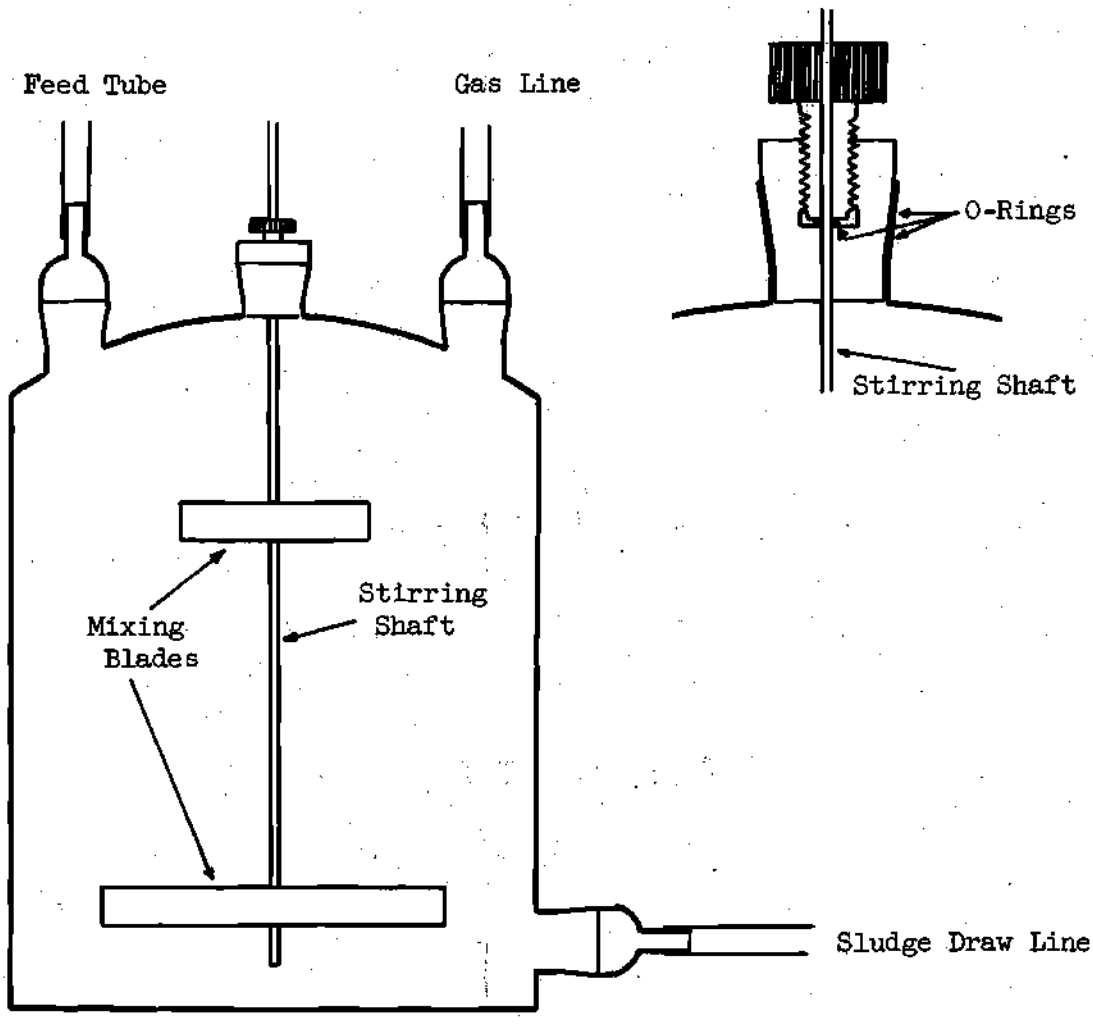


Figure 3. Digestion Bottle, Mixing Seal

stopper. One opening was used to fill the bottle with water and as a water outlet tube; the other opening served as a gas inlet tube. The gas line from the digester was fitted with a T-joint which connected to a simple mercury manometer open to the atmosphere. This manometer contained three platinum electrodes, the second spaced 1/8 inch below the first, and the third about four inches below the second. The electrodes were connected to a relay control, the circuit diagram of which is shown in Figure 4. This relay control was in turn connected to a solonoid valve in the water outlet line.

As gas was produced in the digester, pressure in the system would force the mercury to rise in the manometer and make contact with the upper electrode and actuate the relay control. This would cause the solonoid valve to be opened, allowing water to flow from the gas collection carboy to the displaced water carboy, thus lowering the pressure in the gas system. As this system pressure decreased, the level of mercury in the manometer was lowered, but current continued to pass through the second electrode keeping the relay actuated and the solonoid valve open. When the mercury passed the second electrode, the circuit was broken, the solonoid valve closed, and water ceased to flow. This cycle was repeated when sufficient gas was again produced to cause the mercury to rise in the manometer and actuate the relay control. Spacing of the upper electrodes at 1/8 inch assured maximum pressure in the system of only 1/8 inch mercury, thus minimizing the possibility of gas leakage due to high pressures.

Daily measurements of gas production could then be simply made by measuring the volume of water displaced. The gas collection carboy could be refilled with water by opening the water inlet and gas inlet tubes. When analysis of the produced gas was desired, the gas inlet tube was attached

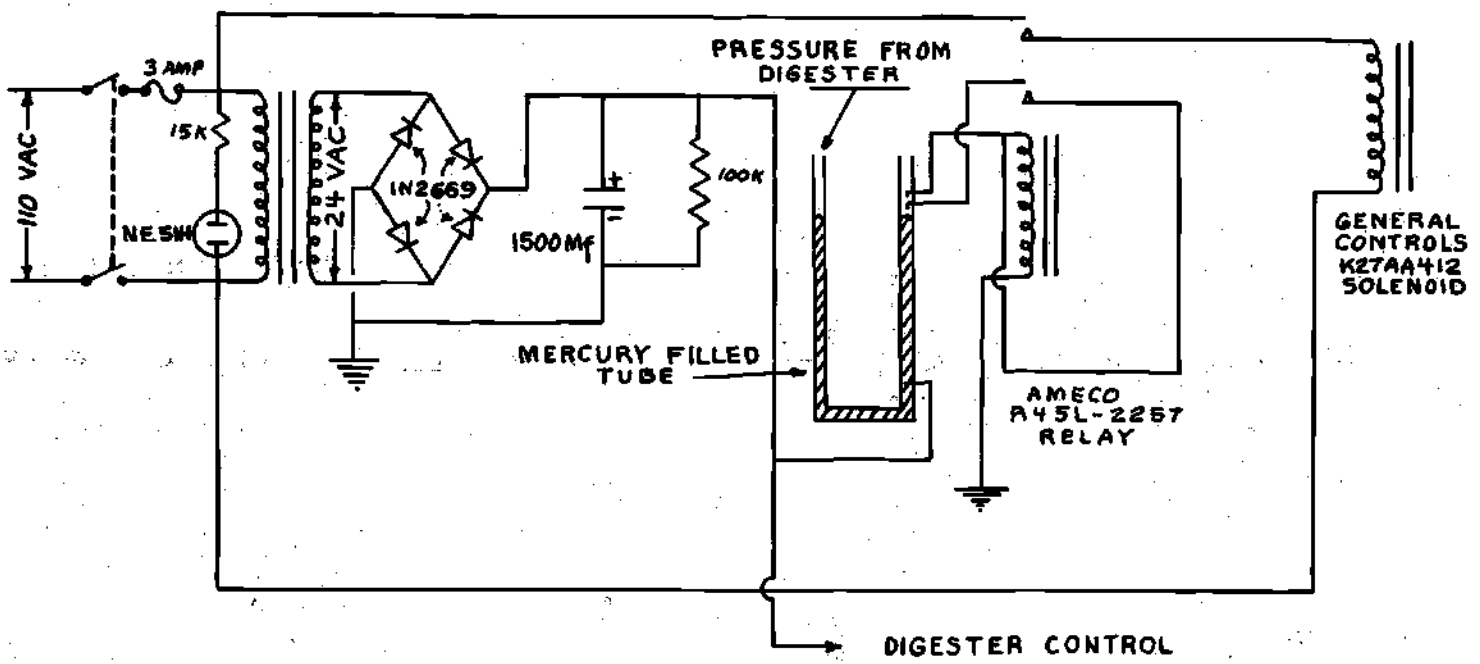


Figure 4. Circuit Diagram for Gas Collection Device

directly to the gas analyzer and the decreased volume caused by refilling the gas bottle forced the gas into the gas analyzer.

Glass fittings and tubes and clear plastic tubing were used in both the water and gas portions of the system. Tight connections were made using wire and lacquer.

The major point of difficulty in maintaining the necessary gas tight system was found to be the seal between the stirring rod and the Woulff bottle. Several arrangements were tried and the illustration of Figure 3 was found to be satisfactory.

CHAPTER IV

ANALYTICAL METHODS

Unless otherwise noted, all laboratory analyses performed during the experimental studies were in accordance with the methods outlined in Standard Methods (46).

The analyses performed on the fresh sludge added to the test digesters were:

(a) Total solids (T.S.)

(b) Volatile solids (V.S.)

The analyses performed on the digested sludge removed from the test units were:

(a) Total solids (T.S.)

(b) Volatile solids (V.S.)

(c) pH

(d) Alkalinity (Alk.: mg/l as $CaCO_3$)

(e) Total volatile acids (V.A.; mg/l as acetic)

(f) Ammonia nitrogen (NH_3-N; mg/l as NH_3)

(g) Dewatering index (D.I.)

Of the sludge removed daily from each of the four digesters, 50 ml were used for total solids and volatile solids determinations; 20 ml were used for NH_3-N determinations; 80 ml were used for alkalinity and volatile acids determinations, and 50 ml were used for the dewatering test.

The gas produced was analyzed daily for CO_2 content using a modification of the Orsat industrial gas analyzer in which a known volume of gas was bubbled through 1ON NaOH and the CO_2-free gas volume noted.

Volatile acids were determined using a modification of the chromatographic technique used by Teletzke and reported by Pohland (6). (See Appendix A.)

A Beckman glass electrode pH meter was employed for pH determinations.

Alkalinity was determined by titrating a sample of centrifuged sludge supernatant to pH 4.3 (methyl orange end-point) with standard sulfuric acid.

The dewatering test was devised for this experiment and is unique in its simplicity. (See Appendix B.) This test purposely was designed so that even the smallest sewage treatment facility - without benefit of vacuum equipment, Buchner funnels, etc., - could routinely determine the character of their sludge relative to its ability to dewater when drying.

In testing for total volatile acids, according to the method described in Appendix A, certain techniques and conditions were noted which should prove to be valuable to future investigators and are reported for their benefit. (See Appendix C.)

CHAPTER V

EXPERIMENTAL PROCUDURE

The experimental equipment was designed and constructed to simulate as closely as practical, the conditions which are to be found in conventional sewage treatment facilities. To make the design considerations valid, operation of the experimental units was planned so as to closely duplicate actual operating conditions.

The only major deviation from conventional operating practice was in the withdrawal of second stage sludge, which will be discussed in its sequence of operation.

Operating temperature was held at 35°C with a deviation of no greater than plus or minus 2°C. As pointed out in Chapter III, system pressure was limited to 1/8 inch of mercury except during servicing when slightly higher pressures were necessary.

Initially, detention times of ten days in first stage and twenty days in second stage were chosen. This was changed later to seven days detention in the first stage units when exceptionally high loading rates were used.

For the first 109 days of operation loading was increased in increments of 0.02 lb of volatile solids per cu ft of digester capacity per day per loading phase. As an example, at a loading rate of 0.20 lb volatile solids per cu ft per day, 550 ml of feed sludge were required. This amount was fed for four days, or one loading phase. On the fifth day, starting a new loading phase, an amount of feed sludge equivalent to 0.22 lb volatile solids

were fed. Commencing at 0.10 lb of volatile solids per cu ft per day, loading was increased approximately each four days. In no case was less than four days at any loading used.

The four digesters were operated as two sets, with a first stage and second stage digester in each set. The first stage units were loaded and operated identically and the second stage units received feed material from the first stage units. The first six days of operation were devoted to start-up of the digesters. Initially, all four units were charged with 3.5 liters each of raw and digested sludge. On each of the following five days 350 ml of sludge was drawn from each unit and 350 ml of feed material added. Approximately six hours after the feed sludge was added, one liter of well mixed sludge from unit one was exchanged with one liter of sludge from unit three. This exchange also was made with the contents of units two and four. This assured that both units of each stage were nearly identical.

At 9:00 a.m. daily, all digesters were serviced and the following procedure was employed.

1. Gas volumes for each unit were measured and recorded.

2. The relay control device was turned off with all solenoid valves in the closed position.

3. The water displacement bottles were emptied and made ready to receive the next 24-hour water displacement.

4. CO_2 content of the gas from each gas reservoir was determined and recorded.

5. The gas reservoirs were refilled with water and the system was made ready to receive gas by closing all vents.

6. The stirring mechanism was started with an initial high velocity then set at operating speed of 60 RPM. The stirrer remained in operation throughout the feeding period.

7. Digested sludge was drawn from each unit in an amount determined by the detention time employed and was placed in receiving flasks.

8. The first stage units were fed a predetermined amount of raw sludge, using water to make up the required volume. The amount to be fed was based on the volatile solids content of the feed material and the loading rate desired. This was calculated as follows:

$$\frac{\text{Loading rate (lb/cu ft)} \times 454 \text{ (gm/lb)} \times \text{digester volume (cu ft)} \times 1000}{\text{volatile solids content of feed (gm/l)}}$$

9. Second stage units were fed the digested sludge from the first stage units, the volume being determined by detention time desired.

10. All gas vents were closed, the system checked for pressure, and the relay control turned on.

11. Digested sludge in the receiving flasks was stored for later analysis.

The servicing required one hour under normal conditions, although two men could work together and cut this to 25 minutes.

The feed sludge was collected when necessary at the Clayton Water Pollution Control Plant of the city of Atlanta. After collection, the primary sludge was passed through a 1/4-inch opening screen and stored at $2^{\circ}C$. On storage at low temperature, the sludge settles and a relative clear supernatant forms above the sludge. Periodically, the supernatant was poured off, and when the sludge was sufficiently high in volatile solids, it was used as feed material.

The Clayton Water Pollution Control Plant was chosen as a source of primary sludge since the character of the sludge at this plant is consistent from week to week and contains limited industrial wastes. To further achieve as great a degree of uniformity of feed material as possible, the raw primary sludge always was collected on Thursday afternoons.

When feeding at very high rates, the feed sludge was so thick that it would not pour, nor would it flow through the 1/2-inch diameter feed tube. To overcome this problem, the measured volume of feed sludge was mixed with a larger amount of draw sludge from the unit to be fed and the mixture was then fed to the units.

At loading rates over 0.46 lb V.S. per cu ft per day it was found necessary to concentrate the feed sludge to a degree greater than that which could be obtained by prolonged settling. To accomplish this, a portion of the feed sludge batch was briefly centrifuged and mixed with the remaining uncentrifuged portion. This mixture contained approximately 16 per cent solids.

During the course of the experimental study observations other than the reported analyses were made. These included visual observation of the digester condition, odor of evolved gas, and character of digested sludge.

In the early phases of operation, three distinct layers in all digesters were noted; a top scum layer, a middle layer of relatively clear liquor, and a bottom section of sludge. This condition prevailed in the second stage units throughout the period of operation. In the first stage units continued increments in loading resulted in a build-up of the bottom layer which continued until no center section was observed. This occurred during the loading range of 0.44 lb V.S. per cu ft per day of digester

capacity at about the 95th day of operation. After this point, the digester contents remained rather consistent in appearance even after a prolonged period of no mixing. There was no visible line of demarcation although the upper section did appear to contain larger particles.

The mechanical mixing which was employed was adequate to mix the contents of the units to a degree considered sufficient. An initial high velocity of the blades would quickly cause the top scum layer to mix with the center section; further stirring resulted in a homogenous condition throughout the unit. When mixing was stopped, settling rapidly built up the sludge layer, while the upper scum layer was formed somewhat more slowly.

At no time was the odor of the evolved gases offensive. No hydrogen sulfide or stale odor was noted, and on several occasions the gas was collected in a displacement flask and was observed to burn with an almost colorless flame.

The study was discontinued at the conclusion of the 0.62 lb V.S. loading range because of mechanical limitations only. To obtain the desired volatile solids loading, the feed sludge required thickening to such an extent that it could no longer be forced into the feed tube and measurement of this thickened sludge lacked earlier accuracy.

CHAPTER VI

EXPERIMENTAL RESULTS

The experimental studies were conducted over a period of 121 days and the basic data obtained during this period is tabulated in Appendix D.

Four experimental units (1, 2, 3, and 4) were operated continuously with respect to loading. Units 1 and 3 were first stage units, while 2 and 4 were second stage units. Unit 2 received its feed material from the draw material of unit 1 and unit 4 received feed from unit 3.

Fresh sludge additions to the first stage units were uniformly increased from 0.10 to 0.62 lb V.S. per cu ft of digester capacity per day. The loading of the second stage units varied from 0.05 to 0.158 lb V.S. per cu ft of digester capacity per day.

On the eighty-fifth day of operation detention time in the first stage units was decreased from ten to seven days. The same volatile solids loading was used for seven days preceding and four days following this change.

On the forty-second day of operation an operational error resulted in the partial flooding, with city water, of all four units. The original operating level was reestablished by drawing off relatively clear supernatant and normal loading practice continued. Contents of first stage units were exchanged for the next three days. Second stage units received the same treatment. This leveled out the deviations caused by the accident.

In order to facilitate subsequent analysis and discussion of the basic data obtained during the study, the data was averaged and separated into twenty-five phases, the limit of each phase being determined by the change in organic loading to the test unit. A summary of the average values at the loading phases is shown in Tables 3, 4, 5, and 6.

As an aid to analysis, the data from Tables 3, 4, 5, and 6 were plotted in Figures 5, 6, 7, and 8. In all graphical presentations of data, an effort has been made to clearly show the break between the two detention periods used. Figures 6 and 7 show the biochemical environment of the second stage units, which were plotted on separate sheets because of the different organic loading which each received as a result of feed material being obtained from the first stage units. Figure 8 is a summary of those indices considered most important with regard to the final digested sludge.

Table 3. Phase Summary of Unit 1

Phase Number	Phase Days	Loading/Day		Biochemical Environment of Unit 1							Gas		% Reduction V.S.
		% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	Cu.Ft./ # V.S. Fed	% CO_2	
1	6-12	1.61	2.50	1.76	2.75	7.10	117	1725		0.53	11.5		
2	13-17	1.94	2.94	1.32	2.70	7.00	238	1815			9.9		32
3	18-23	2.28	3.97	0.89	1.91	6.94	147	1675		0.53	8.1		61
4	24-27	2.58	4.50	0.68	1.40	6.96	118	1720		0.61	6.9		74
5	28-32	2.90	5.07	0.84	1.65	6.94	109	1800	418	0.47	7.1		61
6	33-36	3.22	5.11	1.40	2.96	6.96	82	1960	432	0.47	6.9	24.25	57
7	37-42	3.54	5.60	1.32	2.54	6.96				9.48	7.3	23.30	63
8	43-48	3.85	6.05	1.77	3.33	7.20	86	2720	581	0.29	7.9	25.75	54
9	49-52	4.18	6.29	1.78	3.30	7.18	104	2900	588	0.27	7.2	27.25	57
10	53-56	4.53	6.48	2.01	3.62	7.12	155	3020	717	0.27	5.9	27.75	56
11	57-60	4.79	6.84	2.08	3.82	7.07	179	2910	737	0.23	6.2	25.75	57
12	61-64	5.13	7.33	1.98	3.61	7.21	281	3140	771	0.20	6.7	25.00	61
13	65-68	5.45	9.93	2.33	4.60	7.30	345	3400	754	0.15	7.2	30.00	57
14	69-72	5.84	10.60	2.82	5.53	7.30	440	3690	859	0.17	7.8	30.25	52
15	73-77	6.12	11.18	3.19	7.60	7.24	467	3883	895	0.11	7.4	30.20	48
16	78-84	6.40	11.76	3.19	7.62	7.30	689	4017	1035	0.07	9.8	29.15	50
17	85-88	4.35	5.73	2.89	6.45	7.24	331	4165	1040		9.1	26.00	34
18	89-92	4.53	5.98	2.65	5.95	7.30	282	3833	961	0.08	8.1	27.30	40
19	93-96	4.95	8.96	2.54	6.45	7.20	286	3970	954	0.07	8.1	24.60	49
20	97-100	5.10	9.41	2.75	6.54	7.23	211	4030	955	0.06	8.5	25.00	46
21	101-105	5.40	9.79	2.76	6.83	7.30	181	3895	945	0.06	8.2	22.00	49
22	106-109	5.66	9.99	3.02	7.25	7.32	147	3800	931	0.05	8.1	20.33	47
23	110-113	6.13	10.30	3.02	7.45	7.23	119	3730	946	0.03	8.0	24.00	51
24	114-117	6.55	11.00	3.12	7.63	7.25	183	4030	1055	0.02	9.7	22.75	52
25	118-121	7.00	11.40	3.35	7.97	7.30	333	4605	1162	0.02	9.0	30.50	52

Table 4. Phase Summary of Unit 3

Phase Number	Phase Days	Loading/Day		Biochemical Environment of Unit 3							Gas		% Reduction V.S.
		% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	Cu.Ft./ # V.S. Fed	% CO_2	
1	6-12	1.61	2.50	2.18	4.66	7.10	110	1840		0.46	10.7		
2	13-17	1.94	2.94	1.38	2.88	7.00	120	1810			10.3		29
3	18-23	2.28	3.97	0.71	1.48	6.98	136	1585		0.55	7.8		69
4	24-27	2.58	4.50	0.70	1.00	6.97	140	1670		0.63	6.8		73
5	28-32	2.90	5.07	0.85	1.43	6.94	104	1723	382	0.43	6.9		71
6	33-36	3.22	5.11	1.28	2.44	6.95	78	1900	428	0.36	7.0	24.75	60
7	37-42	3.54	5.60	1.08	2.16	6.97				0.37	8.1	22.00	70
8	43-48	3.85	6.05	1.62	3.12	7.22	70	2540	567	0.26	8.3	26.25	58
9	49-52	4.18	6.29	1.84	3.43	7.20	115	3010	645	0.27	7.7	25.00	56
10	53-56	4.53	6.48	1.73	3.23	7.24	147	3050	737	0.22	6.4	30.25	62
11	57-60	4.79	6.84	2.20	3.82	7.22	183	3027	786	0.15	6.6	28.75	54
12	61-64	5.13	7.33	2.20	4.60	7.30	266	3170	804	0.18	7.1	26.50	57
13	65-68	5.45	9.93	2.75	5.40	7.39	336	3530		0.12	7.6	25.60	50
14	69-72	5.84	10.60	2.82	5.60	7.40	423	2785	896	0.12	8.3	28.50	52
15	73-77	6.12	11.18	3.10	7.06	7.36	408	3927	909	0.09	7.5	29.20	49
16	78-84	6.40	11.76	3.13	8.23	7.40	701	4113	1035	0.07	10.3	26.33	51
17	85-88	4.35	5.73	2.70	6.53	7.38	339	4179	1065		9.2	29.00	38
18	89-92	4.53	5.98	2.51	5.97	7.47	267	3993	965	0.07	8.4	18.30	45
19	93-96	4.95	8.96	2.77	6.64	7.30	165	4035	1005	0.09	8.2	20.60	44
20	97-100	5.10	9.41	2.85	6.77	7.40	192	3985	930	0.07	8.5	19.50	44
21	101-105	5.40	9.79	2.89	6.88	7.40	195	3775	815	0.06	8.0	21.50	47
22	106-109	5.66	9.99	3.23	7.46	7.32	191	3680	888	0.06	8.2	19.33	43
23	110-113	6.13	10.30	3.11	7.68	7.25	193	3710	910	0.04	9.3	18.25	49
24	114-117	6.55	11.00	3.18	8.01	7.27	315	3965	1006	0.02	9.7	24.00	51
25	118-121	7.00	11.40	3.38	8.03	7.25	401	4560	1135	0.02	8.8	29.50	52

Table 5. Phase Summary of Unit 2

		Loading/Day		Biochemical Environment of Unit 2							Gas		
Phase Number	Phase Days	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	Cu.Ft./ # V.S. Fed	% CO_2	% Reduction V.S.
1	6-12	1.61	2.50	2.00	4.32	7.08	136	1855		0.44			
2	13-17	1.94	2.94	1.48	3.12	7.11	153	2010		0.38			24
3	18-23	1.94	2.94	0.97	2.04	7.11	118	1885		0.48			50
4	24-27	1.94	2.94	1.02	2.14	7.10	123	1880		0.33			47
5	28-32	1.94	2.94	9.85	1.90	7.12	113	1837	411	0.44			56
6	33-36	v a r i e d		0.70	1.50	7.09	78	1540	363	0.43		23.5	
7	37-42	v a r i e d		0.72	1.14	7.00				0.53		25.3	
8	43-48	1.77	3.33	0.75	1.49	7.35	56	2180	452	0.41	2.91	17.0	58
9	49-52	1.78	3.30	0.90	1.79	7.26	46	2360	487	0.36	2.86	15.7	50
10	53-56	2.01	3.62	0.87	1.84	7.32	54	2730	633	0.27	2.59	10.3	57
11	57-60	2.08	3.82	1.04	2.22	7.40	51	2780	638	0.29	3.33	7.3	50
12	61-64	1.98	3.61	1.24	2.61	7.48	57	3030	671	0.23	3.51	9.2	37
13	65-68	2.33	4.60	1.42	3.22	7.50	66	3245	691	0.19	3.16	13.2	39
14	69-72	2.82	5.67	1.59	3.24	7.50	52	3445	749	0.22	2.99	14.0	44
15	73-77	3.19	7.60	1.83	4.18	7.42	40	3777	806	0.14	2.51	14.0	43
16	78-84	3.15	7.64	2.15	5.54	7.41	69	4087	891	0.13	3.47	17.4	32
17	85-88	2.89	6.45	2.11	5.60	7.50	46	4400	969		3.18	20.5	28
18	89-92	2.65	5.95	2.33	6.29	7.60	148	4617	1075	0.09	2.53	12.0	12
19	93-96	2.54	6.45	2.38	6.34	7.40	182	4760	1120	0.11	2.07	17.0	6
20	97-100	2.75	6.54	2.39	6.26	7.50	94	4790	1117	0.09	1.92	16.9	13
21	101-105	2.76	6.83	2.22	6.08	7.60	82	4860	1220	0.10	1.88	15.7	20
22	106-109	3.02	7.25	2.23	6.05	7.47	94	4920	1142	0.09	1.81	18.3	26
23	110-113	3.02	7.45	2.11	5.69	7.37	87	4830	1160	0.07	1.86	13.7	30
24	114-117	3.12	7.63	2.25	6.05	7.48	188	4890	1147	0.05	1.91	13.5	28
25	118-121	3.35	7.97	2.25	5.80	7.40	220	5075	1200	0.05	1.83	22.5	33

Table 6. Phase Summary of Unit 4

Phase Number	Phase Days	Loading/Day		Biochemical Environment of Unit 4							Gas		% Reduction V.S.
		% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	Cu.Ft./ # V.S. Fed	% CO_2	
1	6-12	1.61	2.50	2.46	5.38	7.10	129	1860		0.45			
2	13-17	1.94	2.94	1.56	3.36	7.11	138	1890		0.43			20
3	18-23	1.94	2.94	0.60	1.30	7.14	129	1840		0.50			69
4	24-27	1.94	2.94	0.74	1.52	7.09	140	1800		0.40			62
5	28-32	1.94	2.94	0.77	1.78	7.10	131	1767	365	0.47			60
6	33-36	v a r i e d		0.64	2.00	7.01	84	1680	376	0.51		25.0	
7	37-42	v a r i e d		0.68	1.46	6.99				0.48		24.0	
8	43-48	1.62	3.12	0.77	1.58	7.30	62	2160	461	0.36		16.7	52
9	49-52	1.84	3.43	0.95	1.85	7.24	44	2400	522	0.44	2.58	14.5	48
10	53-56	1.73	3.23	0.79	1.62	7.35	67	2650	543	0.43	3.31	19.0	54
11	57-60	2.20	3.82	1.12	2.32	7.42	56	2860	602	0.29	3.13	12.2	49
12	61-64	2.20	4.60	1.36	2.85	7.49	53	3020	685	0.24	3.45	12.6	38
13	65-68	2.75	5.40	1.70	3.37	7.52	66	3275	720	0.19	3.18	12.0	38
14	69-72	2.82	5.60	1.71	3.71	7.52	43	3490	751	0.19	3.02	14.5	39
15	73-77	3.10	7.06	1.93	4.34	7.38	49	3793	828	0.18	2.84	14.4	38
16	78-84	3.13	8.23	2.17	5.55	7.51	74	4113	923	0.13	3.46	14.8	31
17	85-88	2.70	6.53	2.19	5.74	7.55	65	4410	997		3.00	15.0	19
18	89-92	2.51	5.96	2.19	6.00	7.55	122	4613	1045	0.09	2.50	11.3	13
19	93-96	2.77	6.64	2.57	7.00	7.42	98	4635	1035	0.09	2.01	13.3	7
20	97-100	2.85	6.77	2.57	6.78	7.50	134	4715	1100	0.09	2.01	14.5	10
21	101-105	2.89	6.88	2.40	6.27	7.55	155	2750	1140	0.09	2.09	15.7	17
22	106-109	3.23	7.46	2.02	5.33	7.42	139	4760	1125	0.08	1.91	17.3	37
23	110-113	3.11	7.68	2.09	5.59	7.37	144	4800	1115	0.06	2.09	16.7	33
24	114-117	3.18	8.01	2.36	6.32	7.47	175	4850	1137	0.05	2.16	11.7	26
25	118-121	3.38	8.03	2.34	6.36	7.35	200	5035	1227	0.05	2.10	23.0	31

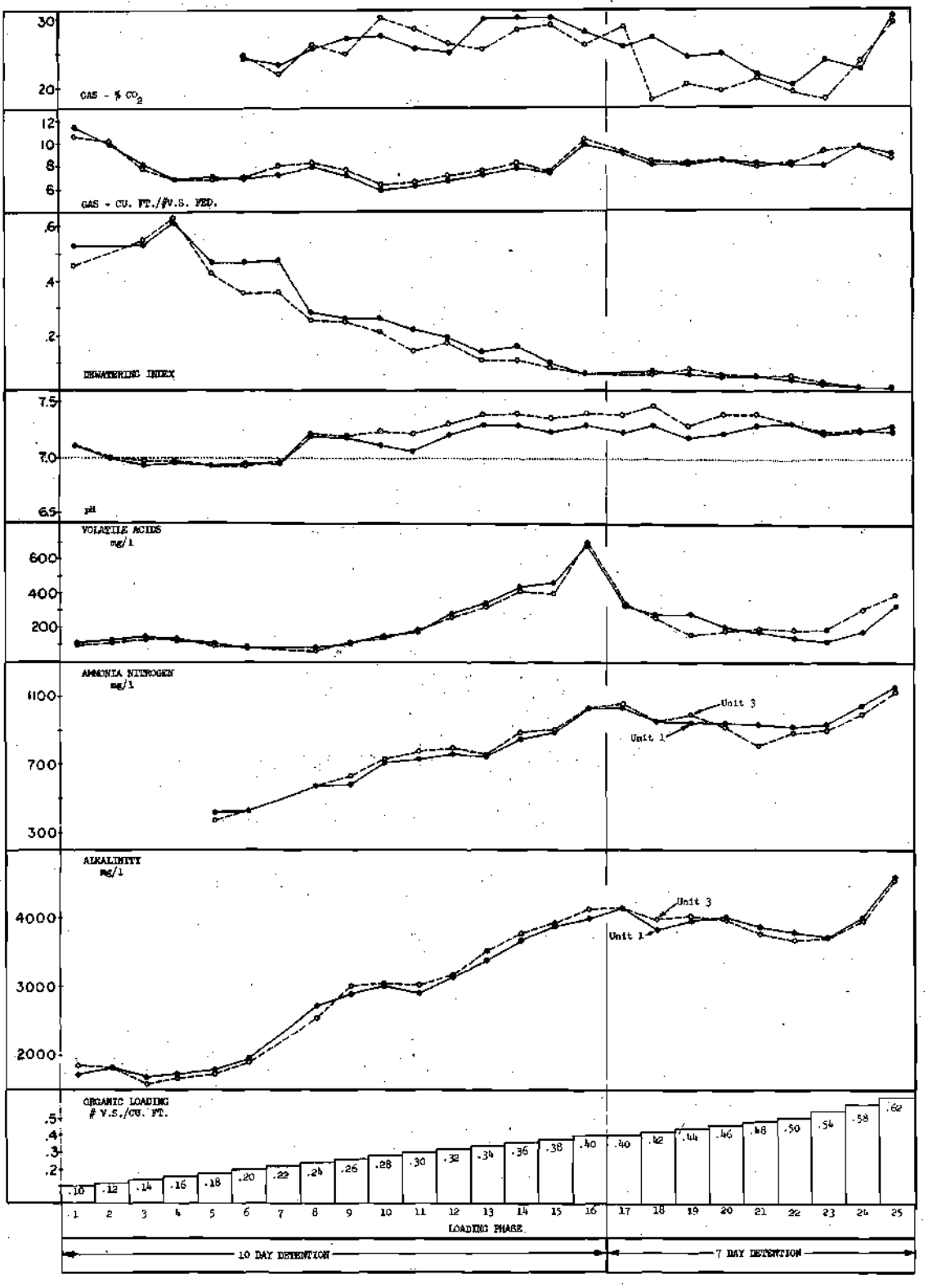


Figure 5. Biochemical Environment, Units 1 and 3

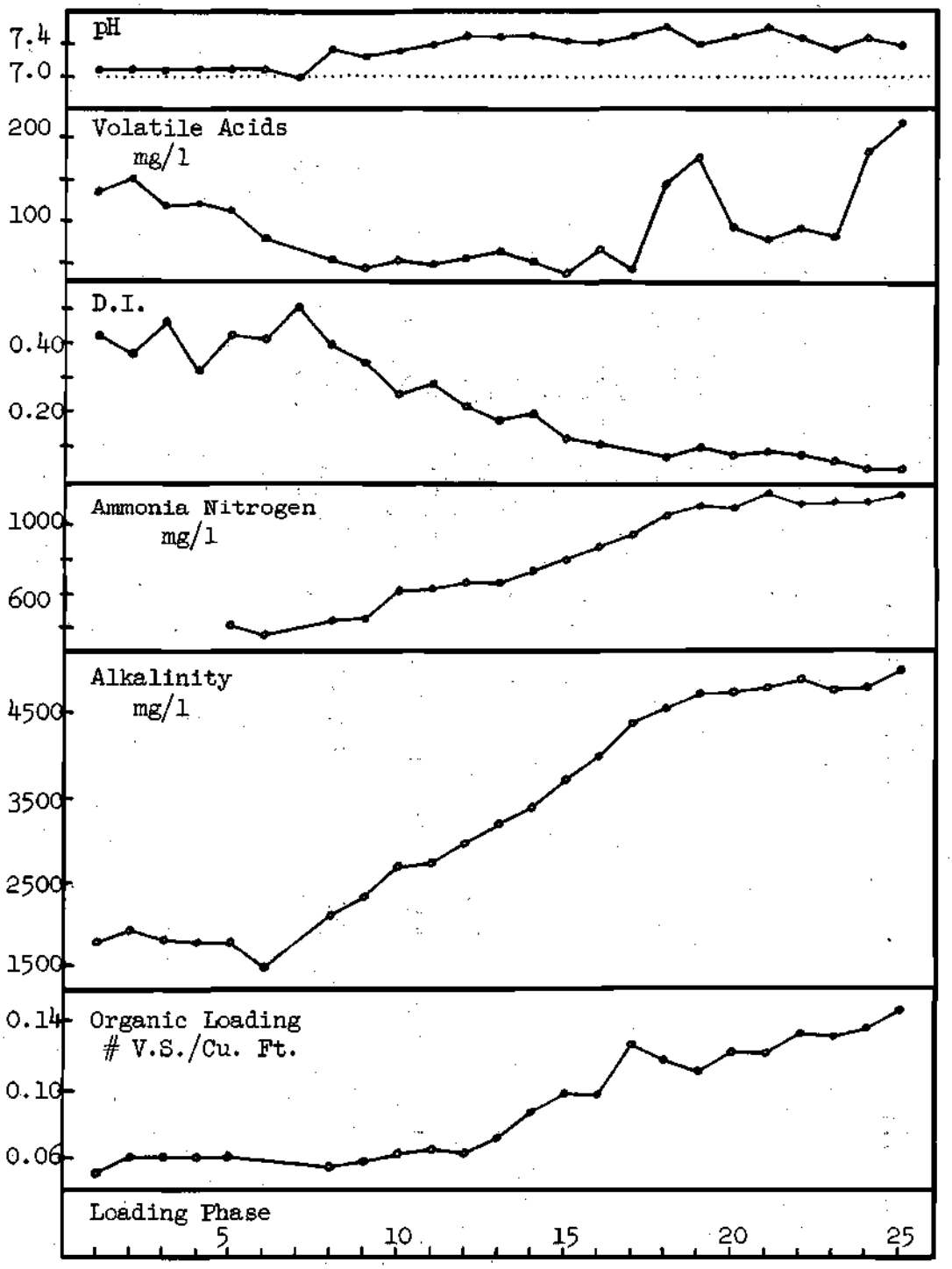


Figure 6. Unit 2 - Biochemical Environment

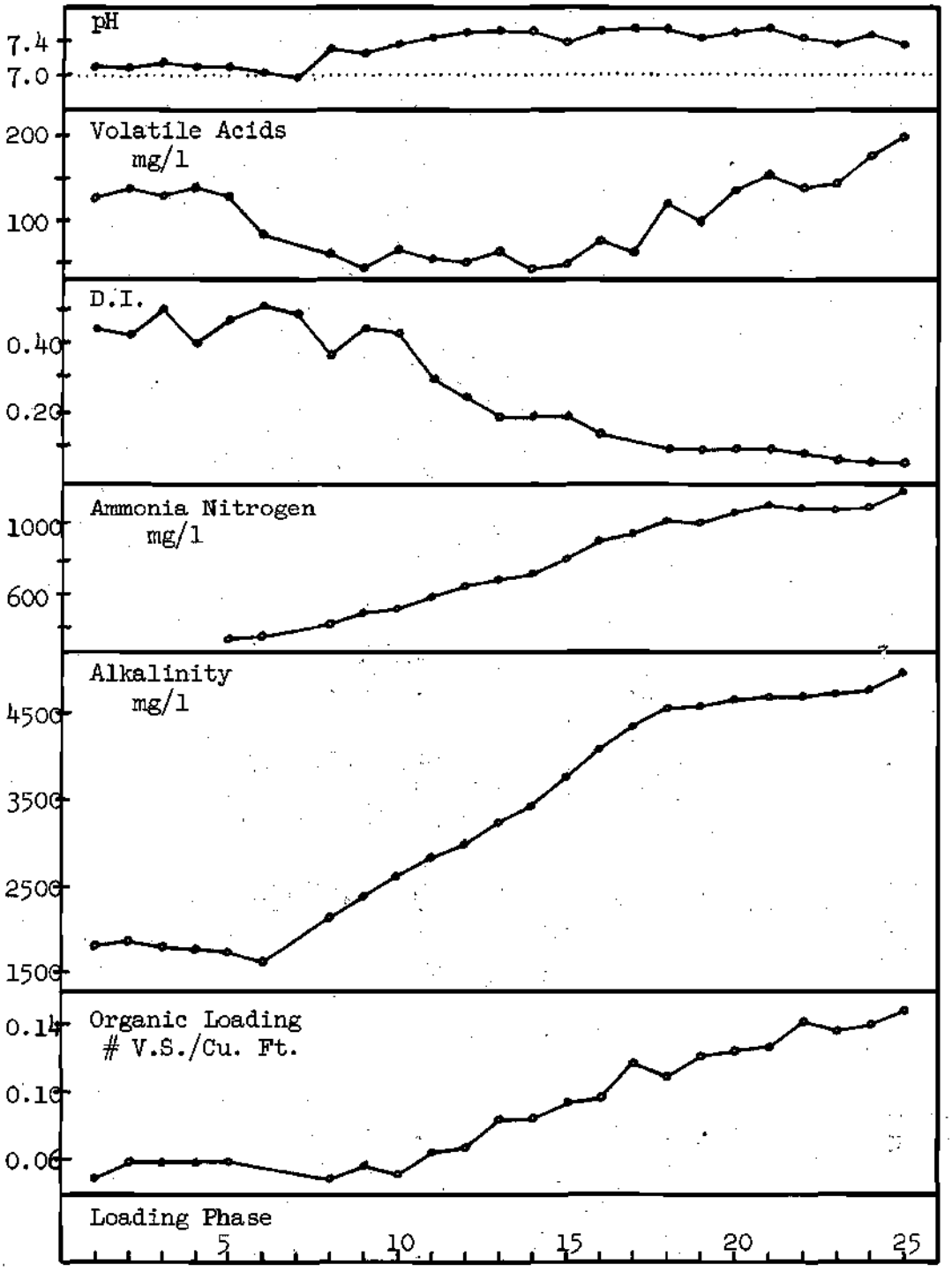


Figure 7. Unit 4 - Biochemical Environment

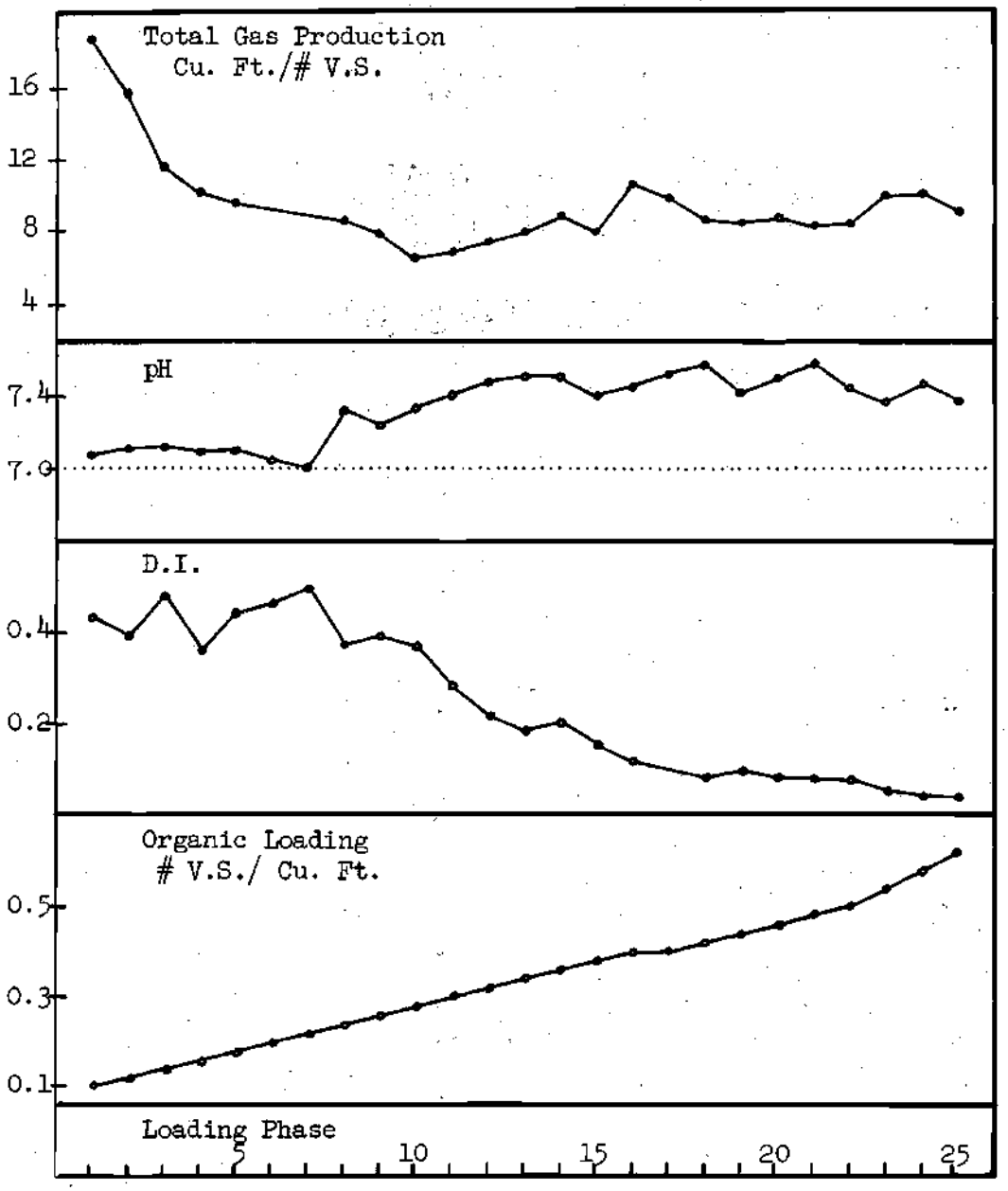


Figure 8. Overall Indices

CHAPTER VII

DISCUSSION OF RESULTS

A comparative study of the graphical data indicates several trends which differ markedly between first and second stage units. To facilitate this presentation, the first and second stage units will be considered separately, followed by a general discussion of the overall results. Figure 5 shows a plot of the first stage results. The near identical results of units 1 and 3 are to be expected considering the operational practices which were followed, but are also indicative of the reliability of the analytical techniques.

The term "retarded" digestion which is used in the following discussion should be considered as being a deflection of the status of the chemical quality of sludge and nature of the by-products. This deflection may be caused by any one or a combination of several factors, including inhibition or excitation of a limited group of organisms which upsets the balance between the groups.

Alkalinity values displayed a steady build-up to the change in feeding practice, then a more or less leveling off effect. The reduction in detention time resulted in a decrease in the ratio of organisms to available food, as well as a change in the overall environment of these organisms. With this change in dention, a different physical character of the sludge was observed and a different level of all soluble by-products was noted.

Had it been possible to continue loading increases with no change in the period of detention, the build-up of alkalinity would probably have continued but at a decreasing rate. This alkalinity increase was caused by the continuing decomposition of nitrogenous materials (increase in ammonia), which is normal in such a system. A further rise in alkalinity values just prior to the conclusion of the study parallels the high values noted at the 0.38 and 0.40 loading ranges for all indices. Again, concentrations of alkalinity increased in a manner typical of nitrogenous matter breakdown.

Volatile acid concentrations varied between 40 and 600 mg per l which is considered normal as reported by Sawyer (36). These relatively low concentrations of volatile acids indicate that a balanced system existed, since the alkaline portion of the system was sufficient to balance the acid portion. There was a slight increase in volatile acids at the 0.38--0.40 and the 0.62 pounds of volatile solids loading ranges, but since these increases occurred immediately prior to changes in detention time in the digesters, further increases in concentration did not develop. If the increases in loading by increasing the concentration of solids could have continued with no change in detention, the volatile acids might have increased to such an extent that the process may have been inhibited. As mentioned in the preceding paragraph, alkalinity concentrations were also increasing at this point, but not at as great a rate. The increase in volatile acid concentration may be caused either by the inability of the methane formers to assimilate all of the acids which are formed or by an increasing rate of formation.

The variation of pH over the entire loading range was minor and recorded values of 7.0 to 7.4 were observed. It is noted that pH values observed during optimum digestion were just slightly over those previously reported (26).

The rate of gas production and percentage of carbon dioxide in the gas were very uniform throughout the study period, except at the 0.62 pound loading level when the CO_2 content showed a marked increase along with a decreased total gas production per pound of volatile solids fed. Since one of the signs of retarded digestion is a decrease in gas production per pound of volatile matter fed as well as an increase in the CO_2 content of this gas, the combination of the two, along with the changes in the other parameters indicated the approach of digestion difficulties.

Ammonia nitrogen increased with loading increases at a fairly even rate. During dosing at the 0.62 pound loading level, however, a high rate of increase in concentration of ammonia occurred. However, decomposition of nitrogenous materials during this period was above normal as indicated by the sharp rise in alkalinity which occurred at this same point in the loading phase.

The dewatering index (D.I.) is discussed in detail in Appendix B. For purposes of discussion at this point, D.I. is indicative of the degree of digestion of the sludge since it reflects the removal of the organic matter which impedes drainage. High values indicate quicker release of fluid, thus a lower concentration of finely dispersed material. The values observed in this study would not be the same for sludges of a different nature, since a high percentage of hydrous and/or fine materials in a sludge would cause less rapid drainage.

The graphical presentation of dewatering index as shown on Figure 5 is striking in its relationship to the organic loading rate. As the organic loading increased beyond 0.18 pounds of volatile solids, the ability of the digested sludge to release its water decreased. This index may be considered

as a direct indication of the extent to which digestion has progressed. It was observed that the D.I. of the second stage sludge was consistently higher than was the D.I. of the first stage sludge at the same loading rate, indicating a more complete digestion as expected.

The decrease in concentrations of alkalinity, volatile acids, and ammonia nitrogen following the change in detention time was caused by the withdrawal of more digester liquor than had been previously removed from the units. This increased withdrawal of liquid volume lowered the concentrations mentioned, but they soon resumed their earlier rates of increase once the newer feeding routines had been established. Even with adequate mixing, the liquid--solid ratio was changed by the increased volume of material withdrawn to such an extent that a new balance was necessary in the units. This balance was achieved naturally, but there was some delay in establishing this new balance.

The results of the second stage units, graphically plotted in Figures 6 and 7, are so closely similar that they may be considered as being identical. As sludge from the first stage units increased in volatile solids, the loading to the second stage units also increased. With this increase of organic loading, increases were noted in the concentrations of alkalinity and ammonia nitrogen. Volatile acid concentration and pH were very constant over the entire loading range. The increases in alkalinity and ammonia nitrogen were caused by the same factors which have been previously discussed.

The overall digestion results are shown in Figure 8, where first stage loading, second stage dewatering ability and pH, and total gas production from both units are shown for the entire experimental period. The dewatering index plot again follows inversely the loading graph.

From the results obtained in this study certain predictions can be made regarding other systems which are operated in a similar fashion. It must be remembered that the high volatile matter feed rates which were used in the latter phases of this study were possible only because of a steady increment to these rates, while commencing at a conventional loading rate. An increase in loading from 0.20 to 0.30 would most likely have been too great an increase for the system to assimilate. However, once a system has been developed at a point above 0.20 lb V.S. per cu ft per day, the following indices are considered valid and indicative of a non-retarded digestion process.

pH	7.0 - 7.5
Gas Production	8 cu ft/lb V.S. fed/day
Alkalinity	2700 mg/l as $CaCO_3$/lb V.S. fed
Ammonia Nitrogen	620 mg/l as NH_3/lb V.S. fed
Dewatering Index	0.30/lb V.S. fed

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

A study has been conducted on the effect of high organic loading rates on mesophilic stage digestion of sewage sludge. Certain conventional digestion indices were measured, and physical observations were included in this study. The conclusions from this study are:

1. Under conditions of adequate mixing and heating, conventional digester loadings can be increased incrementally to at least as high as 0.58 pounds of volatile solids per cubic foot of digester capacity per day without disrupting the balance of the digestion process.

2. Under conditions of adequate mixing and heating, reductions as high as 75 per cent in volatile solids can be achieved at loading in excess of 0.40 pounds of volatile solids per cubic foot of digestion capacity per day, when this loading rate is increased by increments.

3. At conditions of adequate mixing and heating, conventional digesters may be loaded at increments of at least 0.04 pounds of volatile solids per cubic foot of digestion capacity per day, spaced at four day intervals.

The following items are recommended as a logical extension to the work which has been presented:

1. A similar study should be conducted in the mesophilic range, with the following changes: (a) An operating volume and detention time should be chosen which will allow incremental loadings to proceed without change in detention time to at least 1.00 pound of volatile solids per cubic foot of

digestion capacity per day; (b) At no time should the feed material contain more than 15 per cent total solids.

2. A similar study should be conducted in the thermophilic range, utilizing those changes noted in item 1.

It is not likely that raw sludge with concentrations as great as 15 per cent would ever be used in sludge digestion because of the high viscosity of this material. The pumping of such sludge is not feasible at this time, nor can such concentrations be economically obtained on a plant scale. In addition, considerable difficulty was experienced in measuring and feeding sludge of this solids concentration.

Both of the previous recommendations should be conducted with the realization that at higher loading rates, increases in volatile acid concentrations will develop which can be of such magnitude as to inhibit the activity of the methane forming organisms, unless they are neutralized. If the first stage does not supply this neutralizing capacity, an effort should be made to use the supernatant liquor from the second stage unit as a source of neutralization potential.

APPENDICES

APPENDIX A

TOTAL VOLATILE ACIDS BY COLUMN CHROMATOGRAPHY

Reagents

1. Silicic acid - a 200 mesh high purity power is mixed with distilled water in a 1-liter beaker making a thick slurry. Decant and remove the supernatant. Add more H_2O, mix well and decant. Repeat two or three times. Remove as much water as possible and place in 103°C oven until dry. Store in desiccator.

2. Thymol Blue indicator - dissolve 0.4g Thymol Blue in 100 ml of freshly boiled H_2O.

3. 10N H_2SO_4

4. 0.5N H_2SO_4

5. 0.02N H_2SO_4

6. Phenolphthalein indicator

7. NaOH in ethanol - add about 0.75 ml of 15-18N NaOH to 1 liter of absolute ethanol. Standardize to about 0.015N NaOH with 0.02N H_2SO_4.

8. Solvents - mix all necessary reagents in a separatory funnel and allow water and organic layers to separate. Drain off lower organic layer through filter paper into a completely dry bottle.

CB_{10}: 360 ml $CHCl_3$ + 40 ml N-Butanol + 80 ml 0.5N H_2SO_4

Procedure

Preparation of Sample

1. Centrifuge or vacuum filter about 50 ml of sludge.

2. Collect the supernatant in a small beaker and discard the sludge.

3. Add a few drops of Thymol Blue indicator to the supernatant.

4. Add 10N H_2SO_4 dropwise until the sample is just red to Thymol Blue. (pH 1.2-2.8).

Total Volatile Acids Determination

1. Place 10 gm of silicic acid in the Gooch or fritted glass crucible. Pack the silicic acid by applying suction to the flask.

2. Place 5 ml of the acidified sample on the silicic acid column. Apply suction momentarily to draw the sample into the column.

3. Add 100 ml of CB_{10} to the top of the column, drawing the solvent through the column with suction into the filtering flask.

4. Titrate the filtrate to a phenolphthalein end-point with approximately 0.015N NaOH in absolute ethyl alcohol. The sample may be mixed during titration by bubbling nitrogen or CO_2-free air through it. (CO_2-free air may be obtained passing air through lime water or Ascarite.)

5. Titrate in a similar manner a blank sample composed of 5 ml of acidified distilled water extracted with 100 ml of CB_{10}.

Total Volatile Acids (mg/l as acetic) = $12{,}000N(a-b)$,

where N = normality of base (NaOH in ethyl alcohol)

a = titer of sample (ml)

b = titer of blank (ml)

APPENDIX B

DEWATERING INDEX

Theory

The process by which sludge loses its moisture may be considered to have two distinct phases. Initially, drainage through the sludge and underlying media; and finally, evaporation to the atmosphere. Evaporation, to a great extent, will depend on local weather conditions and must naturally vary greatly from locale to locale. However, drainage can be determined regardless of weather and provides reliable, consistent results which can be interpreted as the dewatering ability of a sludge. With reasonably frequent sampling and testing even the smallest facility will be able to adequately judge the character of sludge.

Apparatus

4 - 100 ml graduated cylinders

4 - 100 ml graduated funnels

Filter paper, Whatman #41 (11 cm dia)

Procedure

Fold filter paper into standard cone shape, place in funnel and spray until damp with distilled water, allowing paper to dry in shape of cone. At time zero, pour 50 ml of well mixed digested sludge into cone formed by filter paper. At 15 minutes record ml of filtrate which has collected in the graduate. At an elapsed time of 60 minutes record the ml of filtrate which has collected in the graduate.

Calculations

$$\frac{2(\text{ml collected in 15 min}) + (\text{ml collected in 60 min})}{150}$$

This arbitrary scale is based on a maximum value of 1.00.

Example:

11 ml collected in 15 min, 25 ml collected in 60 min

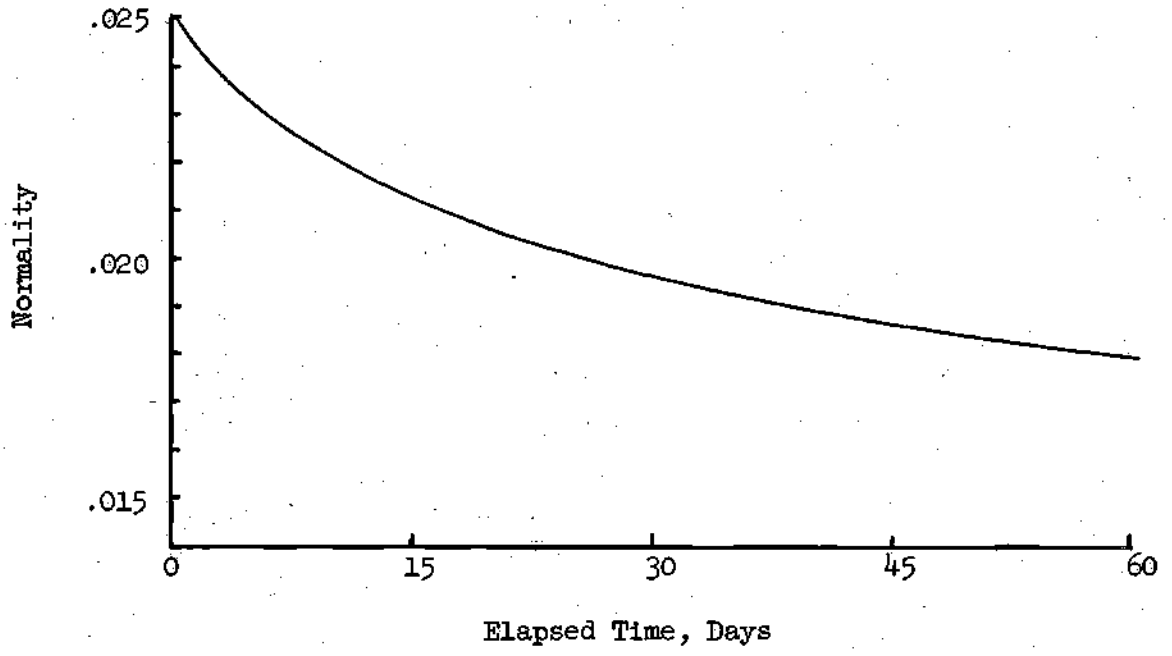
$$\frac{2(11) + (25)}{150} = 0.31$$

APPENDIX C

OBSERVATIONS ON THE VOLATILE ACID DETERMINATION METHOD

NaOH in ethanol, the titrant to be used in the volatile acid determination procedure, decreases in normality with time even without exposure to atmospheric CO_2. This titrant is rather difficult to work with, plugging micro-curettes and deteriorating Tygon tubing.

The decrease of normality with time was found to follow the pattern shown in the following figure. This record was compiled over a 60 day period.



The NaOH in ethanol was sotred in two containers, one of clear flint glass and the other of dark red flint glass. The determined values did not show significant variation for the two different type containers.

The titrant could well be reacting with the silica of the containers and the use of some of the inert plastics for containers could be used for storage, thereby alleviating the normality decrease.

In compiling the data on this decrease in normality periodic checks were made to insure that the overall technique and reagents used were satisfactory. These checks consisted of making up a sample of acetic acid in water at a known concentration and making a determination of the acid concentration by the routine chromatographic technique. This actually served as a double check on technique and on titrant normality.

The use of absolute ethyl alcohol as a titrant is most expensive, even for a small facility. It is entirely possible that 95 per cent ethyl alcohol, or methyl alcohol could be substituted at a rather sizeable saving.

APPENDIX D-1. Summary of Basic Digestion Data, Unit 1

	Loading Per Day			Biochemical Environment of Unit 1							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
6	0.10	1.61	2.50			7.1	117	1725			7.7	
7	0.10	1.61	2.50	1.76	2.74						8.8	
8	0.10	1.61	2.50								8.2	
9	0.10	1.61	2.50								8.2	
10	0.10	1.61	2.50								8.0	
11	0.10	1.61	2.50			7.0					7.5	
12	0.10	1.61	2.50	1.32	2.70	6.9	128	1815		0.53	8.0	
13	0.12	1.94	2.94								7.8	
14	0.12	1.94	2.94								7.9	
15	0.12	1.94	2.94			7.0					8.8	
16	0.12	1.94	2.94			7.0					8.7	
17	0.12	1.94	2.94			7.0					8.5	
18	0.14	2.28	3.97	1.20	2.68	7.1	142	1680		0.45	7.6	
19	0.14	2.28	3.97			6.9					8.8	
20	0.14	2.28	3.97								7.9	
21	0.14	2.28	3.97	0.58	1.14	6.8	153	1670		0.62	6.8	
22	0.14	2.28	3.97			6.9					7.8	
23	0.14	2.28	3.97			7.0					8.8	
24	0.16	2.58	4.50			7.0					9.0	
25	0.16	2.58	4.50	0.68	1.40	7.0	118	1720		0.61	7.0	
26	0.16	2.58	4.50			6.9						
27	0.16	2.58	4.50			6.9					7.3	
28	0.18	2.90	5.07	0.66	1.42	6.9	103	1755		0.53	8.1	
29	0.18	2.90	5.07			7.0	97	1795			8.4	
30	0.18	2.90	5.07	0.86	1.64	7.0	115	1815			9.2	
31	0.18	2.90	5.07			6.9					8.9	
32	0.18	2.90	5.07	1.00	1.88	6.9	102	1840	418	0.42	10.5	

APPENDIX D-1. (Continued)

	Loading Per Day			Biochemical Environment of Unit 1							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
33	0.20	3.22	5.11			6.9					9.9	23
34	0.20	3.22	5.11			7.0			394		9.6	26
35	0.20	3.22	5.11	1.40	2.96	7.0	82	1960	470		10.0	21
36	0.20	3.22	5.11			6.9				0.47	9.4	27
37	0.22	3.54	5.60	1.32	2.54	6.9					10.3	27
38	0.22	3.54	5.60			6.9					9.5	20
39	0.22	3.54	5.60			6.8				0.48	12.9	23
40	0.22	3.54	5.60			7.2					12.2	
41	0.22	3.54	5.60								11.9	
42	0.22	3.54	5.60									
43	0.24	3.85	6.05									
44	0.24	3.85	6.05			7.2					12.5	
45	0.24	3.85	6.05	1.80	3.34	7.2			581		12.0	23
46	0.24	3.85	6.05			7.1	86	2720		0.29	15.0	24
47	0.24	3.85	6.05	1.74	3.32	7.2					13.4	28
48	0.24	3.85	6.05			7.2					13.5	28
49	0.26	4.18	6.58	1.82	3.40	7.2	92	2840	532	0.37	14.1	27
50	0.26	4.18	6.58			7.1					14.4	24
51	0.26	4.18	6.00	1.74	3.20	7.2	115	2960	645		12.3	26
52	0.26	4.18	6.00			7.2					11.9	32
53	0.28	4.53	6.48	1.98	3.56	7.2	150	2940	714	0.27	11.7	28
54	0.28	4.53	6.48			7.0					11.4	26
55	0.28	4.53	6.48			7.1					11.6	29
56	0.28	4.53	6.48	2.04	3.68	7.2	161	3100	720		11.9	28
57	0.30	4.79	6.84			7.1	150	2860			12.8	25
58	0.30	4.79	6.84	2.08	3.82	7.0	148	2900	765	0.23	12.6	27
59	0.30	4.79	6.84			7.1					12.1	27

APPENDIX D-1. (Continued)

	Loading Per Day			Biochemical Environment of Unit 1							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
60	0.30	4.79	6.84			7.1	240	2960	708		14.7	24
61	0.32	5.13	7.33	1.90	3.40	7.2	261	3080		0.21	14.2	24
62	0.32	5.13	7.33			7.2					14.7	26
63	0.32	5.13	7.33	2.06	3.82	7.2	302	3200	771	0.18	15.9	27
64	0.32	5.13	7.33			7.2					15.6	23
65	0.34	5.45	9.93	2.00	3.90	7.2	314	3320				28
66	0.34	5.45	9.93			7.3					16.3	28
67	0.34	5.45	9.93	2.66	5.30	7.4	376	3480	754	0.15		34
68	0.34	5.45	9.93			7.3					18.1	30
69	0.36	5.84	10.60	2.56	5.14	7.2	393	3590	850	0.17	19.8	30
70	0.36	5.84	10.60			7.2					19.0	31
71	0.36	5.84	10.60	3.08	6.20	7.3	487	3800	868		20.6	28
72	0.36	5.84	10.60			7.3					19.4	32
73	0.38	6.12	11.18	3.18	8.44	7.2	477	3760	870	0.11	19.6	30
74	0.38	6.12	11.18			7.3						28
75	0.38	6.12	11.18	3.20	6.76	7.3	423	3940	890		18.6	29
76	0.38	6.12	11.18			7.1					20.0	33
77	0.38	6.12	11.18			7.3	500	3950	926		21.3	31
78	0.40	6.40	11.76			7.3					22.5	27
79	0.40	6.40	11.76	3.24	7.92	7.3	725	3940	945		25.3	31
80	0.40	6.40	11.76			7.3					27.0	27
81	0.40	6.40	11.76	3.10	7.68	7.3	682	3940	1000	0.07	29.5	33
82	0.40	6.40	11.76			7.3					29.5	29
83	0.40	6.40	11.76	3.22	7.26	7.3	661	4170	1160		28.2	26
84	0.40	6.40	11.76			7.3					26.0	24
85	0.40	4.35	5.73	2.84	6.46	7.2	400	4310	1020		27.7	30
86	0.40	4.35	5.73			7.3					24.6	

APPENDIX D-1. (Continued)

	Loading Per Day			Biochemical Environment of Unit 1							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
87	0.40	4.35	5.73	2.94	6.44	7.2	262	4060	1060		25.6	
88	0.40	4.35	5.73			7.2					24.6	22
89	0.42	4.53	5.98	2.86	6.54	7.3	232	3880	980	0.08	25.0	29
90	0.42	4.53	5.98			7.3	254	3940			22.4	26
91	0.42	4.53	5.98	2.78	6.00	7.3					23.0	27
92	0.42	4.53	5.98	2.32	5.30	7.3	360	3880	942		24.7	
93	0.44	4.95	8.96			7.2					24.3	24
94	0.44	4.95	8.96	2.42	6.52	7.2	334	3960	924	0.07	25.0	23
95	0.44	4.95	8.96			7.2					23.2	27
96	0.44	4.95	8.96	2.66	6.38	7.1	238	3980	985		28.0	
97	0.46	5.10	9.41			7.3					27.8	21
98	0.46	5.10	9.41	2.76	6.54	7.2	220	4060	995		25.8	25
99	0.46	5.10	9.41			7.2				0.06	28.0	24
100	0.46	5.10	9.41	2.74	6.54	7.2	202	4000	916		28.7	30
101	0.48	5.40	9.79			7.2					27.2	
102	0.48	5.40	9.79	2.72	6.80	7.3	192	3910	925		27.7	12
103	0.48	5.40	9.79			7.3				0.06	27.8	22
104	0.48	5.40	9.79	2.80	6.86	7.4	170	3880	965		27.8	
105	0.48	5.40	9.79			7.3					28.0	22
106	0.50	5.66	9.99	2.98	7.08	7.4	155	3820	945		26.6	21
107	0.50	5.66	9.99			7.3				0.05	28.1	19
108	0.50	5.66	9.99	3.06	7.42	7.3	140	3780	917		30.9	
109	0.50	5.66	9.99			7.3					28.8	21
110	0.54	6.13	10.30			7.1					39.7	23
111	0.54	6.13	10.30	2.98	7.46	7.2	125	3680	938		36.8	24
112	0.54	6.13	10.30			7.3				0.03	37.6	21
113	0.54	6.13	10.30	3.06	7.44	7.3	114	3780	955		37.1	28

APPENDIX D-1. (Continued)

	Loading Per Day			Biochemical Environment of Unit 1							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
114	0.58	6.55	11.00			7.2					39.0	25
115	0.58	6.55	11.00	3.12	7.60	7.2	158	3960	1010		40.5	22
116	0.58	6.55	11.00			7.2				0.02	41.1	23
117	0.58	6.55	11.00	3.12	7.66	7.3	208	4100	1100		37.8	21
118	0.62	7.00	11.40			7.3					42.3	25
119	0.62	7.00	11.40	3.34	8.02	7.3	305	4410	1100		37.6	23
120	0.62	7.00	11.40			7.3				0.02	41.0	36
121	0.62	7.00	11.40	3.36	7.92	7.3	360	4800	1225		35.4	38

APPENDIX D-2. Summary of Basic Digestion Data, Unit 3

	Loading Per Day			Biochemical Environment of Unit 3							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
6	0.10	1.61	2.50			7.1	110	1840			7.7	
7	0.10	1.61	2.50	2.18	4.66						6.9	
8	0.10	1.61	2.50								6.2	
9	0.10	1.61	2.50								8.2	
10	0.10	1.61	2.50								6.1	
11	0.10	1.61	2.50			7.0					8.0	
12	0.10	1.61	2.50	1.38	2.88	7.1	120	1810		0.46	9.6	
13	0.12	1.94	2.94			7.0					7.6	
14	0.12	1.94	2.94			6.9					9.5	
15	0.12	1.94	2.94			7.0					8.5	
16	0.12	1.94	2.94			6.9					9.0	
17	0.12	1.94	2.94			7.0					8.7	
18	0.14	2.28	3.97	0.90	1.94	7.1	136	1620		0.57	8.0	
19	0.14	2.28	3.97			7.0					8.3	
20	0.14	2.28	3.97								7.6	
21	0.14	2.28	3.97	0.52	1.02	6.9	1.40	1550		0.53	6.7	
22	0.14	2.28	3.97			6.9					6.8	
23	0.14	2.28	3.97			7.0					8.6	
24	0.16	2.58	4.50			6.9					8.9	
25	0.16	2.58	4.50	0.70	1.00	7.0	122	1670		0.63	6.9	
26	0.16	2.58	4.50			7.0						
27	0.16	2.58	4.50			6.9					7.1	
28	0.18	2.90	5.07	0.76	1.06	6.8	111	1710		0.53	8.5	
29	0.18	2.90	5.07			7.0	110	1710			8.1	
30	0.18	2.90	5.07	0.88	1.62	7.0	100	1730			8.9	
31	0.18	2.90	5.07			7.0					8.2	
32	0.18	2.90	5.07	0.90	1.62	6.9	95	1740	382	0.33	9.8	

APPENDIX D-2. (Continued)

	Loading Per Day			Biochemical Environment of Unit 3							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
33	0.20	3.22	5.11			6.9					9.6	23
34	0.20	3.22	5.11			7.0			423		9.5	27
35	0.20	3.22	5.11	1.28	2.44	6.9	78	1900	433		10.3	23
36	0.20	3.22	5.11			6.9				0.36	10.0	26
37	0.22	3.54	5.60	1.08	2.16	6.9					11.6	24
38	0.22	3.54	5.60			6.9					10.4	23
39	0.22	3.54	5.60			6.9				0.57	14.2	19
40	0.22	3.54	5.60			7.2					13.8	
41	0.22	3.54	5.60								12.9	
42	0.22	3.54	5.60									
43	0.24	3.85	6.05									
44	0.24	3.85	6.05			7.3					13.4	
45	0.24	3.85	6.05	1.62	3.08	7.2			567		12.5	22
46	0.24	3.85	6.05			7.2	70	2540		0.26	15.6	27
47	0.24	3.85	6.05	1.62	3.16	7.2					14.0	25
48	0.24	3.85	6.05			7.3					14.3	31
49	0.26	4.18	6.58	1.92	3.56	7.2	100	2880	630	0.27	15.0	25
50	0.26	4.18	6.58			7.2					15.2	22
51	0.26	4.18	6.00	1.76	3.30	7.2	120	3040	660		13.2	23
52	0.26	4.18	6.00			7.2					12.9	30
53	0.28	4.53	6.48	1.68	3.16	7.2	146	3000	834	0.22	12.9	31
54	0.28	4.53	6.48			7.1					12.3	33
55	0.28	4.53	6.48			7.3					12.9	31
56	0.28	4.53	6.48	1.78	3.30	7.4	148	3100	740		12.5	26
57	0.30	4.79	6.84			7.2	162	2980			13.7	25
58	0.30	4.79	6.84	2.20	3.82	7.2	167	3000	778	0.15	13.7	31
59	0.30	4.79	6.84			7.2					12.8	30

APPENDIX D-2. (Continued)

	Loading Per Day			Biochemical Environment of Unit 3							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
60	0.30	4.79	6.84			7.3	220	3100	794		15.1	29
61	0.32	5.13	7.33	2.08	3.66	7.3	240	3080		0.21	14.8	27
62	0.32	5.13	7.33			7.3					16.3	31
63	0.32	5.13	7.33	2.32	5.54	7.4	292	3260	804	0.15	16.7	23
64	0.32	5.13	7.33			7.2					16.2	25
65	0.34	5.45	9.93	3.12	6.02	7.3	310	3440				25
66	0.34	5.45	9.93			7.4					17.2	26
67	0.34	5.45	9.93	2.38	4.78	7.4	363	3620		0.12		26
68	0.34	5.45	9.93			7.4					19.0	26
69	0.36	5.84	10.60	2.72	5.34	7.4	387	3670	882	0.12	20.8	29
70	0.36	5.84	10.60			7.4					20.3	31
71	0.36	5.84	10.60	2.92	5.86	7.4	460	3900	910		21.2	25
72	0.36	5.84	10.60			7.4					21.7	29
73	0.38	6.12	11.18	2.94	7.14	7.4	392	3800	920	0.093	20.4	30
74	0.38	6.12	11.18			7.4						28
75	0.38	6.12	11.18	3.26	6.98	7.4	3.8	4000	890		19.6	29
76	0.38	6.13	11.18			7.2					19.6	27
77	0.38	6.12	11.18			7.4	514	3980	919		20.2	32
78	0.40	6.40	11.76			7.4						
79	0.40	6.40	11.76	3.18	7.88	7.4	733	3920	952		26.6	29
80	0.40	6.40	11.76			7.3					29.0	28
81	0.40	6.40	11.76	3.18	8.74	7.4	730	4060	1030	0.07	30.6	31
82	0.40	6.40	11.76			7.4					30.2	23
83	0.40	6.40	11.76	3.02	8.06	7.5	640	4360	1124		29.3	23
84	0.40	6.40	11.76			7.4					28.7	24
85	0.40	4.35	5.73	2.58	6.48	7.3	392	4340	1080		29.2	31
86	0.40	4.35	5.73			7.3					25.0	

APPENDIX D-2. (Continued)

	Loading Per Day			Biochemical Environment of Unit 3							Gas	
Day	#V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
87	0.40	4.35	5.73	2.82	6.58	7.4	287	4000	1050		25.4	
88	0.40	4.35	5.73			7.3					24.0	27
89	0.42	4.53	5.98	2.46	6.02	7.5	234	4020	995	0.07	24.0	19
90	0.42	4.53	5.98			7.4	190	4020			24.1	20
91	0.42	4.53	5.98	2.54	5.76	7.5					25.8	16
92	0.42	4.53	5.98	2.54	6.12	7.5	310	3940	935		24.9	
93	0.44	4.95	8.96			7.5					25.8	15
94	0.44	4.95	8.96	2.76	6.64	7.3	159	4070	1085	0.09	24.8	21
95	0.44	4.95	8.96			7.2					24.0	26
96	0.44	4.95	8.96	2.78	6.64	7.2	172	4000	925		27.3	
97	0.46	5.10	9.41			7.4					28.3	17
98	0.46	5.10	9.41	2.82	6.56	7.4	180	3990	955		25.8	20
99	0.46	5.10	9.41			7.4				0.07	28.2	20
100	0.46	5.10	9.41	2.88	6.98	7.4	204	3980	906		28.0	21
101	0.48	5.40	9.79			7.4					25.9	
102	0.48	5.40	9.79	2.78	6.78	7.4	199	3830	845		26.9	22
103	0.48	5.40	9.79			7.4				0.06	28.2	21
104	0.48	5.40	9.79	3.00	6.98	7.4	192	3720	785		27.2	
105	0.48	5.40	9.79			7.4					26.5	13
106	0.50	5.66	9.99	3.18	7.34	7.4	189	3720	909		27.3	17
107	0.50	5.66	9.99			7.3				0.06	30.4	19
108	0.50	5.66	9.99	3.28	7.58	7.3	193	3640	868		30.5	
109	0.50	5.66	9.99			7.3					28.3	22
110	0.54	6.13	10.30			7.2				0.04	33.8	18
111	0.54	6.13	10.30	3.18	7.74	7.2	190	3680	903		35.8	20
112	0.54	6.13	10.30			7.3					35.1	16
113	0.54	6.13	10.30	3.04	7.62	7.3	196	3740	917		37.3	19

APPENDIX D-2. (Continued)

	Loading Per Day			Biochemical Environment of Unit 3							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
114	0.58	6.55	11.00			7.2					40.7	20
115	0.58	6.55	11.00	3.14	8.00	7.3	322	3860	1040		39.4	25
116	0.58	6.55	11.00			7.3				0.02	41.3	24
117	0.58	6.55	11.00	3.22	8.02	7.3	308	4070	973		36.9	27
118	0.62	7.00	11.40			7.3					42.0	22
119	0.62	7.00	11.40	3.18	8.06	7.2	312	4340	1070		38.3	24
120	0.62	7.00	11.40			7.2				0.02	36.7	33
121	0.62	7.00	11.40	3.58	8.00	7.3	490	4780	1200		36.0	39

APPENDIX D-3. Summary of Basic Digestion Data, Unit 2

	Loading Per Day			Biochemical Environment of Unit 2							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
6	.05	1.61	2.50			7.1	136	1855			6.0	
7	.05	1.61	2.50	2.00	4.32						5.7	
8	.05	1.61	2.50								5.1	
9	.05	1.61	2.50								6.0	
10	.05	1.61	2.50								4.0	
11	.05	1.61	2.50			7.0					4.5	
12	.05	1.61	2.50	1.48	3.12	7.1	153	2010		0.44	5.3	
13	.06	1.94	2.94								4.5	
14	.06	1.94	2.94								5.6	
15	.06	1.94	2.94			7.1					5.4	
16	.06	1.94	2.94			7.1					4.8	
17	.06	1.94	2.94			7.2					5.1	
18	.06	1.94	2.94	1.24	2.68	7.3	162	1940		0.38	4.0	
19	.06	1.94	2.94			7.0					4.3	
20	.06	1.94	2.94								4.0	
21	.06	1.94	2.94	0.70	1.40	7.3	74	1830		0.44	3.4	
22	.06	1.94	2.94			7.0					3.8	
23	.06	1.94	2.94			7.0					4.4	
24	.06	1.94	2.94			7.0					5.1	
25	.06	1.94	2.04	1.02	2.14	7.3	123	1880		0.33	3.7	
26	.06	1.94	2.94			7.1						
27	.06	1.94	2.94			7.0					3.0	
28	.06	1.94	2.94	1.02	2.18	7.0	134	1860		0.41	3.6	
29	.06	1.94	2.94			7.1	118	1835			3.4	
30	.06	1.94	2.94	0.84	1.74	7.3	110	1825			3.4	
31	.06	1.94	2.94			7.1					3.7	
32	.06	1.94	2.94	0.70	1.78	7.0	92	1830	411	0.46	4.2	

APPENDIX D-3 (Continued)

	Loading Per Day			Biochemical Environment of Unit 2							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
33	.06	1.94	2.94			7.1					4.9	18
34	v a r i e d					7.1			376		3.1	26
35	v a r i e d			0.70	1.50	7.1	78	1540	351		2.7	22
36	v a r i e d					7.1				0.43	2.3	28
37	v a r i e d			0.72	1.14	7.0					2.1	24
38	v a r i e d					6.9					1.9	19
39	v a r i e d					6.9				0.53	2.3	33
40	v a r i e d					7.2					2.0	
41	v a r i e d										1.9	
42	v a r i e d											
43	v a r i e d											
44	v a r i e d					7.4					1.2	
45	.056	1.80	3.34	0.78	1.58	7.3			452		1.2	13
46						7.3	56	2180		0.41	1.1	16
47	.054	1.74	3.32	0.72	1.40	7.3					1.1	20
48						7.4					1.0	19
49	.057	1.82	3.40	0.90	1.76	7.3	42	2280	478	0.36	1.1	16
50						7.2					1.2	17
51	.054	1.74	3.20	0.90	1.82	7.3	51	2440	496		1.1	17
52						7.3					1.0	13
53	.061	1.98	3.56	0.88	1.86	7.3	48	2620	672	0.27	1.0	
54						7.2					1.1	10
55						7.3					1.1	10
56	.063	2.04	3.68	0.86	1.82	7.5	60	2840	594		1.3	11
57						7.4	57	2540			1.6	7
58	.064	2.08	3.82	1.04	2.22	7.4	43	2860	613	0.29	1.4	5
59						7.4					1.4	

APPENDIX D-3 (Continued)

	Loading Per Day			Biochemical Environment of Unit 2							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
60						7.4	52	2940	663		1.6	10
61	.059	1.90	3.40	1.16	2.34	7.5	59	3000		0.29	1.6	8
62						7.5					1.5	11
63	.064	2.06	3.82	1.32	2.88	7.5	55	3060	671	0.18	1.6	8
64						7.4					1.4	10
65	.062	2.00	3.90	1.42	3.22	7.4	62	3180			1.5	12
66						7.5					1.4	11
67	.082	2.66	5.30	1.42	3.22	7.6	70	3310	691	0.19	1.8	16
68						7.5					1.7	14
69	.079	2.56	5.14	1.58	3.10	7.5	49	3380	742	0.22	1.7	15
70						7.5					1.7	15
71	.095	3.08	6.20	1.60	3.38	7.5	56	3510	756		2.0	11
72						7.5					1.9	15
73	.098	3.18	8.44	1.72	4.16	7.4	30	3600	785	0.14	2.0	16
74						7.5					1.2	15
75	.099	3.20	6.76	1.94	4.20	7.5	43	3760	805		1.8	15
76						7.2					2.0	16
77						7.5	46	3870	828		1.8	8
78						7.4						15
79	.100	3.24	7.92	2.12	5.28	7.4	44	4020	860		1.8	15
80						7.5					2.1	14
81	.096	3.10	7.68	2.18	6.00	7.4	84	4040	895	0.13	2.3	18
82						7.4					2.3	21
83	.100	3.22	7.26	2.16	5.34	7.4	79	4200	920		3.1	18
84						7.5					2.9	20
85	.126	2.84	6.46	2.12	5.86	7.4	46	4380	965		3.1	21
86						7.5					2.7	

APPENDIX D-3 (Continued)

	Loading Per Day			Biochemical Environment of Unit 2							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	% CO_2
87	.130	2.94	6.44	2.10	5.34	7.6	46	4420	973		2.8	
88						7.5					2.4	20
89	.126	2.86	6.54	2.18	5.90	7.6	48	4520	1060	0.09	2.2	6
90						7.6	46	4640			2.0	12
91	.123	2.78	6.00	2.26	5.86	7.6					2.1	12
92	.103	2.32	5.30	2.54	7.12	7.6	352	4690	1090		2.0	
93						7.6					1.8	4
94	.107	2.42	6.52	2.56	6.92	7.4	210	4760	1110	0.11	1.6	21
95						7.3					1.5	14
96	.118	2.66	6.38	2.20	5.76	7.3	155	4760	1130		1.6	
97						7.5					1.6	20
98	.122	2.76	6.54	2.12	5.30	7.5	114	4780	1100		1.6	17
99						7.5				0.09	1.7	16
100	.122	2.74	6.54	2.66	7.22	7.5	74	4800	1135		1.7	14
101						7.5					1.5	
102	.121	2.72	6.80	2.04	5.66	7.5	83	4830			1.7	12
103						7.6				0.10	1.6	14
104	.124	2.80	6.86	2.40	6.50	7.6	82	4860	1220		1.5	
105						7.7					1.8	21
106	.132	2.98	7.08	2.28	6.10	7.7	96	4900	1155		1.6	16
107						7.4				0.09	1.7	14
108	.135	3.06	7.42	2.18	6.00	7.4	92	4940	1130		1.8	
109						7.4					1.7	25
110						7.3					1.8	12
111	.132	2.98	7.46	2.02	5.28	7.4	90	4820	1170		1.8	23
112						7.4				0.07	1.7	15
113	.136	3.06	7.44	2.20	6.10	7.4	85	4840	1150		1.7	14

APPENDIX D-3 (Continued)

	Loading Per Day			Biochemical Environment of Unit 2							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
114						7.4						15
115	.138	3.12	7.60	2.16	5.54	7.5	258	4840	1090		1.8	12
116						7.5				0.05	2.0	14
117	.138	3.12	7.66	2.34	6.56	7.5	118	4940	1205		1.9	13
118						7.4					1.8	17
119	.148	3.34	8.02	2.26	6.00	7.4	150	4990	1155		1.8	17
120						7.4				0.05	2.1	19
121	.149	3.36	7.92	2.24	5.60	7.4	291	5160	1245		1.9	28

APPENDIX D-4. Summary of Basic Digestion Data, Unit 4

	Loading Per Day			Biochemical Environment of Unit 4							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
6	.05	1.61	2.50			7.1	129	1860			7.4	
7	.05	1.61	2.50	2.46	5.38						6.2	
8	.05	1.61	2.50								4.8	
9	.05	1.61	2.50								6.1	
10	.05	1.61	2.50								5.6	
11	.05	1.61	2.50			7.0					5.2	
12	.05	1.61	2.50	1.56	3.36	7.2	138	1890		0.45	5.3	
13	.06	1.94	2.94								4.6	
14	.06	1.94	2.94								5.6	
15	.06	1.94	2.94			7.1					5.2	
16	.06	1.94	2.94			7.1					4.8	
17	.06	1.94	2.94			7.2					5.1	
18	.06	1.94	2.94	0.84	1.82	7.3	159	1930		0.43	3.3	
19	.06	1.94	2.94			7.0					4.3	
20	.06	1.94	2.94								3.9	
21	.06	1.94	2.94	0.36	0.78	7.2	99	1750		0.50	3.4	
22	.06	1.94	2.94			7.0					3.7	
23	.06	1.94	2.94			7.1					4.7	
24	.06	1.94	2.94			7.0					5.5	
25	.06	1.94	2.94	0.74	1.52	7.3	140	1800		0.40	3.5	
26	.06	1.94	2.94			7.1						
27	.06	1.94	2.94			7.0					3.1	
28	.06	1.94	2.94	0.94	2.06	7.0	162	1790		0.43	3.8	
29	.06	1.94	2.94			7.1	129	1770			3.6	
30	.06	1.94	2.94	0.66	1.78	7.3	137	1770			3.9	
31	.06	1.94	2.94			7.1					3.7	
32	.06	1.94	2.94	0.72	1.50	7.0	97	1740	365	0.51	4.5	

APPENDIX D-4 (Continued)

	Loading Per Day			Biochemical Environment of Unit 4							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
33	.06	1.94	2.94			7.0					3.9	24
34	v a r i e d					7.0			368		3.0	26
35	v a r i e d			0.64	2.00	7.0	84	1680	384		2.8	21
36	v a r i e d					7.0				0.51	2.5	29
37	v a r i e d			0.68	1.46	6.9					2.3	24
38	v a r i e d					6.9					2.1	25
39	v a r i e d					6.9				0.48	2.4	23
40	v a r i e d					7.2					2.1	
41	v a r i e d										2.0	
42	v a r i e d											
43	v a r i e d											
44	v a r i e d					7.4					1.4	
45	.050	1.62	3.08	0.80	1.62	7.3			461		1.3	13
46						7.3	62	2160		0.36	1.4	18
47	.050	1.62	3.16	0.74	1.54	7.2					1.2	19
48						7.3					1.1	17
49	.059	1.92	3.56	0.92	1.76	7.2	47	2280	518	0.44	1.0	17
50						7.2					1.2	15
51	.055	1.76	3.30	0.98	1.94	7.3	42	2520	527		0.9	13
52						7.3					1.0	13
53	.052	1.68	3.16	0.80	1.62	7.4	63	2520	536	0.43	1.0	15
54						7.3					1.3	21
55						7.3					1.2	22
56	.055	1.78	3.30	0.78	1.62	7.4	72	2780	550		1.4	18
57						7.5	58	2780			1.5	12
58	.068	2.20	3.82	1.12	2.32	7.4	49	2860	588	0.29	1.4	9
59						7.4					1.5	16

APPENDIX D-4 (Continued)

	Loading Per Day			Biochemical Environment of Unit 4							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
60						7.4	61	2940	616		1.6	12
61	.064	2.08	3.66	1.24	2.42	7.5	53	2980		0.26	1.6	14
62						7.5					1.7	12
63	.072	2.32	5.54	1.48	3.28	7.5	53	3060	685	0.23	1.7	12
64						7.4					1.6	12
65	.097	3.12	6.02	1.62	3.46	7.4	65	3220			1.7	9
66						7.5					1.8	13
67	.074	2.38	4.78	1.78	3.28	7.6	67	3330	720	0.19	2.2	13
68						7.6					1.9	13
69	.084	2.72	5.34	1.66	3.42	7.6	36	3400	727	0.19	2.0	14
70						7.6					1.7	13
71	.090	2.92	5.86	1.76	3.90	7.5	51	3580	775		1.9	16
72						7.4					1.8	15
73	.091	2.94	7.14	1.86	4.26	7.4	46	2660	805	0.18	1.8	16
74						7.4					2.3	14
75	.101	3.26	6.98	2.00	4.42	7.4	56	3800	825		1.8	16
76						7.2					2.0	15
77						7.5	46	3920	855		0.7	11
78						7.5						12
79	.099	3.18	7.88	2.20	5.18	7.6	55	4020	895		1.8	16
80						7.5					2.4	12
81	.098	3.18	8.74	2.18	5.70	7.5	96	4080	910	0.13	2.1	15
82						7.5					2.4	18
83	.098	3.02	8.06	2.12	5.68	7.5	72	4240	963		2.9	15
84						7.5					2.7	16
85	.114	2.58	6.48	2.12	5.84	7.5	80	4400	1000		2.6	16
86						7.5					2.4	

APPENDIX D-4 (Continued)

	Loading Per Day			Biochemical Environment of Unit 4							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
87	.125	2.82	6.58	2.26	5.64	7.7	51	4420	994		2.4	
88						7.5					2.4	12
89	.108	2.46	6.02	2.12	5.72	7.6	78	4580	1040	0.09	2.1	10
90						7.6	41	4660			1.9	11
91	.113	2.54	5.76	2.20	5.68	7.5					1.9	13
92	.112	2.54	6.12	2.26	6.60	7.5	247	4600	1050		1.9	
93						7.6					1.8	15
94	.122	2.76	6.64	2.62	7.20	7.5	142	4610	990	0.09	1.8	8
95						7.3					1.7	17
96	.123	2.78	6.64	2.52	6.80	7.3	53	4660	1080		1.9	
97						7.4					1.8	17
98	.125	2.82	5.65	2.74	7.22	7.5	102	4710	1080		1.7	18
99						7.6				0.09	1.8	15
100	.128	2.88	6.98	2.40	6.34	7.5	165	4720	1120		1.8	8
101						7.5					1.8	
102	.123	2.78	6.78	2.70	7.42	7.5	160	4740			2.0	18
103						7.6				0.09	1.8	17
104	.133	3.00	6.98	2.10	5.12	7.6	151	4760	1140		1.8	
105						7.4					2.0	12
106	.141	3.18	7.34	2.00	5.18	7.7	141	4760	1140		1.9	21
107						7.4				0.08	2.1	17
108	.146	3.28	7.58	2.04	5.48	7.4	137	4760	1110		1.9	
109						7.4					1.8	14
110						7.3					1.8	16
111	.141	3.18	7.74	2.08	5.52	7.4	143	4800	1110		2.0	13
112						7.4				0.06	2.1	17
113	.134	3.04	7.62	2.10	5.66	7.4	145	4800	1120		2.2	21

APPENDIX D-4 (Continued)

	Loading Per Day			Biochemical Environment of Unit 4							Gas	
Day	# V.S./ Cu. Ft.	% V.S.	% T.S.	% V.S.	% T.S.	pH	V.A.	Alk.	NH_3-N	D.I.	L/Day	$\%CO_2$
114						7.4					2.2	10
115	.139	3.14	8.00	2.30	6.00	7.5	145	4820	1140		2.2	12
116						7.5				0.05	2.2	12
117	.142	3.22	8.02	2.42	6.64	7.5	205	4880	1135		2.0	13
118						7.4					2.3	22
119	.141	3.18	8.06	2.32	6.68	7.3	135	4960	1175		2.2	21
120						7.3				0.05	2.3	19
121	.158	3.58	8.00	2.36	6.04	7.4	265	5110	1280		2.0	30

BIBLIOGRAPHY

Literature Cited

(1) Pohland, F. G., "General Review of Literature on Anaerobic Sewage Sludge Digestion," Engineering Bulletin of Purdue University (Engineering Extension Series 110), 46, No. 5, 1962.

(2) Rudolfs, W. and Gehm, J. W., "Chemical Composition of Sewage Sludges, with Particular Reference to Their Phosphoric Acid Content," New Jersey Agricultural Experiment Station Bulletin, No. 699, 1942.

(3) Imhoff, K., Sewage Treatment, John Wiley and Sons, Inc., New York, 1956.

(4) Buswell, A. M., "Fundamentals of Anaerobic Treatment of Organic Wastes," Sewage and Industrial Wastes, 29, 717, 1957.

(5) Heukelekian, H., Biological Treatment of Sewage and Industrial Wastes, Vol. II, 25-43, Reinhold Publishing Corporation, New York, 1958.

(6) Pohland, F. G., Laboratory Investigations on the Thermological Aspects and Volatile Acids-Alkalinity Behavior During Anaerobic Sludge Digestion, Ph. D. Thesis, Purdue University, 1961.

(7) Langford, L. L., Mesophilic Anaerobic Digestion, Second Waste Treatment Conference, Manhattan College, New York, April 1957.

(8) Buswell, A. M., "Studies of Two-Stage Sludge Digestion," Illinois State Water Survey Bulletin, 29, 1929.

(9) McKinney, R. E., Microbiology for Sanitary Engineers, McGraw-Hill Book Company, Incorporated, New York, 1962.

(10) Sawyer, C. N., Howard, F. S., Pershe, E. R., "Scientific Basis for Liming of Digesters," Sewage and Ind. Wastes, 26, 935, 1954.

(11) Fair, G. M., Moore, E. W., and Thomas, H. A., "The Natural Purification of River Muds and Pollutional Sediments," Sewage Works Journal, 13, 1209, 1941.

(12) Stanier, R. Y., Doudoroff, M., and Adelberg, E. A., The Microbial World, Prentice-Hall, Incorporated, Englewood Cliffs, New Jersey, 1957.

(13) Buck, T. C., Keefer, C. E., and Hatch, H., "Bacteriological Studies of Sludge Digestion, I. A Faculative Anaerobe Isolated from Digested Sludge," Sewage and Ind. Wastes, 25, 993, 1953.

(14) Golueke, C. G., "Temperature Effects on Anaerobic Digestion of Raw Sewage Sludge," Sewage and Ind. Wastes, 30, 1225, 1958.

(15) Garber, W. F., "Plant-Scale Studies of Thermophilic Digestion at Los Angeles," Sewage and Ind. Wastes, 26, 1202, 1954.

(16) Rudolfs, W. and Heukelekian, H., "Thermophilic Digestion of Sewage Solids," Industrial and Engineering Chemistry, 23, 67, 1931.

(17) Shafer, S. W., "Initial Digester Start-up at Alexandria, Virginia," Sewage and Ind. Wastes, 29, 1190, 1957.

(18) Fuhrman, R. E., "Scum Control in Sludge Digestion," Sewage and Ind. Wastes, 26, 453, 1954.

(19) Keefer, C. E., "Effects of Premixing Raw and Digested Sludge on High-Rate Digestion," Sewage and Ind. Wastes, 31, 388, 1959.

(20) Steel, E. W., Water Supply and Sewerage, McGraw-Hill Book Company, New York, 1960.

(21) Schreiber, H. A., "Digester Mixing," Journal, Water Pollution Control Federation, 34, 513, 1962.

(22) Guarino, C. F., "Sludge Digestion Experiences in Philadelphia," J. Water Pol. Con. Fed., 35, 626, 1963.

(23) Heukelekian, H. and Berger, M., "Value of Culture and Enzyme Additives in Promoting Digestion," Sewage and Ind. Wastes, 25, 1259, 1953.

(24) Grune, W. N. and Sload, R. W., "Biocatalysts in Sludge Digestion," Sewage and Ind. Wastes, 26, 1425, 1954.

(25) McCarty, P. L. and McKinney, R. E., "Salt Toxicity in Anaerobic Digestion," J. Water Pol. Con. Fed., 33, 399, 1961.

(26) Cassell, E. A. and Sawyer, C. N., "A Method of Starting-up High-Rate Digesters," Sewage and Ind. Wastes, 31, 123, 1959.

(27) Kaplovsky, A. J., "Volatile Acid Production During the Digestion of Seeded, Unseeded, and Limed Fresh Solids," Sewage and Ind. Wastes, 23, 713, 1951.

(28) Barker, H. A., "Biological Formation of Methane," Ind. and Eng. Chem., 48, 1438, 1956.

(29) Schulze, K. L. and Raju, B. N., "Studies on Sludge Digestion and Methane Fermentation -- II. Methane Fermentation of Organic Acids," Sewage and Ind. Wastes, 30, 164, 1958.

(30) Keefer, C. E., Buck, T. C. and Hatch, H., "Bacteriological Studies of Sludge Digestion -- II. Optimum pH at which Sludge Digests when Inoculated with Streptococcus Diploidus," Sewage and Ind. Wastes, 25, 1174, 1953.

(31) Keefer, C. E., Buck, T. C. and Hatch, H., "Bacteriological Studies of Sludge Digestion -- III. Effect of Different Quantities of Streptococcus Diploidus on Sludge Digestion," Sewage and Ind. Wastes, 25, 1406, 1953.

(32) Mueller, L. E. et al., "Some Characteristics of Anaerobic Sludge Digestion -- I. Effect of Loading," Sewage and Ind. Wastes, 31, 669, 1959.

(33) Schultz, K. L., "Studies on Sludge Digestion and Methane Fermentation -- I. Sludge Digestion at Increased Solids Concentration," Sewage and Ind. Wastes, 30, 28, 1958.

(34) "Interpretation of Sewage Treatment Plant Tests - A Panel Discussion," Sewage and Ind. Wastes, 31, 92, 1959.

(35) Sawyer, C. N., Chemistry for Sanitary Engineers, McGraw-Hill Book Company, Incorporated, New York, 1960.

(36) Mueller, H. F., Larson, T. E., and Lennary, W. J., "Chromatographic Identification and Determination of Organic Acids in Water," Analytical Chemistry, 30, 41, 1958.

(37) Mueller, H. F., Buswell, A. M., and Larson, T. E., "Chromatographic Determination of Volatile Acids," Sewage and Ind. Wastes, 28, 255, 1956.

(38) Elsden, S. R., "The Application of the Silica Gel Partition Chromatogram to the Estimation of Volatile Fatty Acids," Biochemical Journal, 40, 252, 1946.

(39) Frook, J. E., "Volatile Acids by Direct Phosphoric Acid Distillation," Sewage and Ind. Wastes, 29, 18, 1957.

(40) Heukelekian, H. and Kaplovsky, A. J., "Improved Method of Volatile Acid Recovery from Sewage Sludges," Sewage Works J., 21, 974, 1949.

(41) Ramsey, L. L. and Patterson, W. I., "Separation and Identification of the Volatile Saturated Fatty Acids (C_1 to C_4)," Association of Official Agricultural Chemists, 28, 644, 1945.

(42) Buswell, A. M., Boring, J. R., and Milam, J. R., "A Paper Chromatographical Method for Volatile Acids," J. Water Pol. Con. Fed., 32, 721, 1960.

(43) DiLallo, R. and Albertson, O. E., "Volatile Acids by Direct Titration," J. Water Pol. Con. Fed., 33, 356, 1961.

(44) Manganelli, R. M. and Brofazi, F. R., "Quantitative Determination of Volatile Acids by Paper Chromatography for Application to Sewage Sludge Digestion," Anal. Chem., 29, 1441, 1957.

(45) Standard Methods for the Examination of Water and Wastewater, American Public Health Association, Incorporated, New York, 1960.

(46) Albertson, O. E., "Ammonia Nitrogen and the Anaerobic Environment," J. Water Pol. Con. Fed., 33, 978, 1961.

(47) Nash, N. and Chasick, A. H., "High-Rate Digester Performance at Jamaica," J. Water Pol. Con. Fed., 32, 526, 1960.

(48) Babbitt, A. E. and Baumann, E. R., Sewerage and Sewage Treatment, John Wiley and Sons, Incorporated, New York, 1958.

(49) McCarty, P. L. and McKinney, R. E., "Volatile Acid Toxicity in Anaerobic Digestion," J. Water Pol. Con. Fed., 33, 223, 1961.

(50) Pohland, F. G. and Bloodgood, D. E., "Laboratory Studies on Mesophilic and Thermophilic Anaerobic Sludge Digestion," J. Water Pol. Con. Fed., 33, 223, 1961.